Review of Injection Schemes

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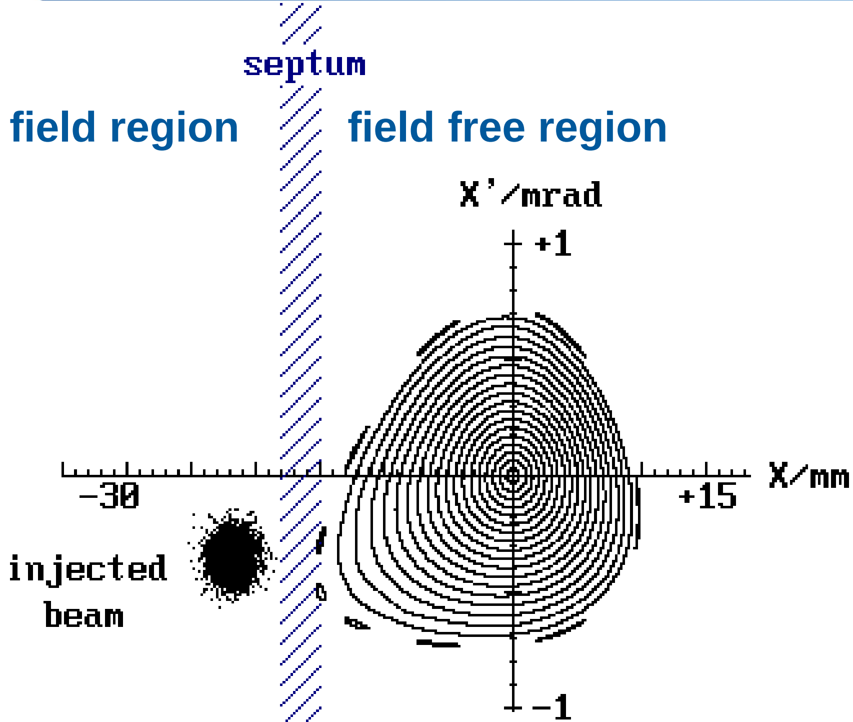
Content

I. Injection – Septum Magnets
II. 4-Kicker Bump – Comment on Optimum Injection Twiss Parameters
III. 3-Kicker Bumps – 2 Different Schemes and with Anti-Septum – Comment on Bump Closure
IV. Single Kicker Injection
V. Single Kicker Swap-Out Injection
VI. Non-Linear Single Kicker Injection
VII. Injection into the Longitudinal Phase Space
VIII. Shifting Excessive Momentum to Other Degrees of Freedom
IX. Summary

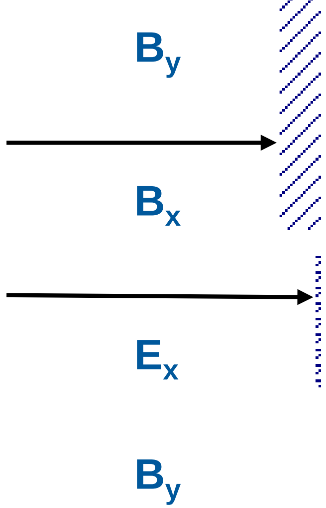


In principle beam can be injected into any coordinates of the 6D-phase space.

Bring beam to be injected as close as possible to the stable phase space of the already stored beam

The closer the better and the easier the final step to merge both beams:

- thinner septa
- smaller emittance of injected beam



P. Lebasque, et al., "Eddy Current Septum Magnets for Booster Injection and Extraction, and Storage Ring Injection at Synchrotron SOLEIL", Proceedings of EPAC'06

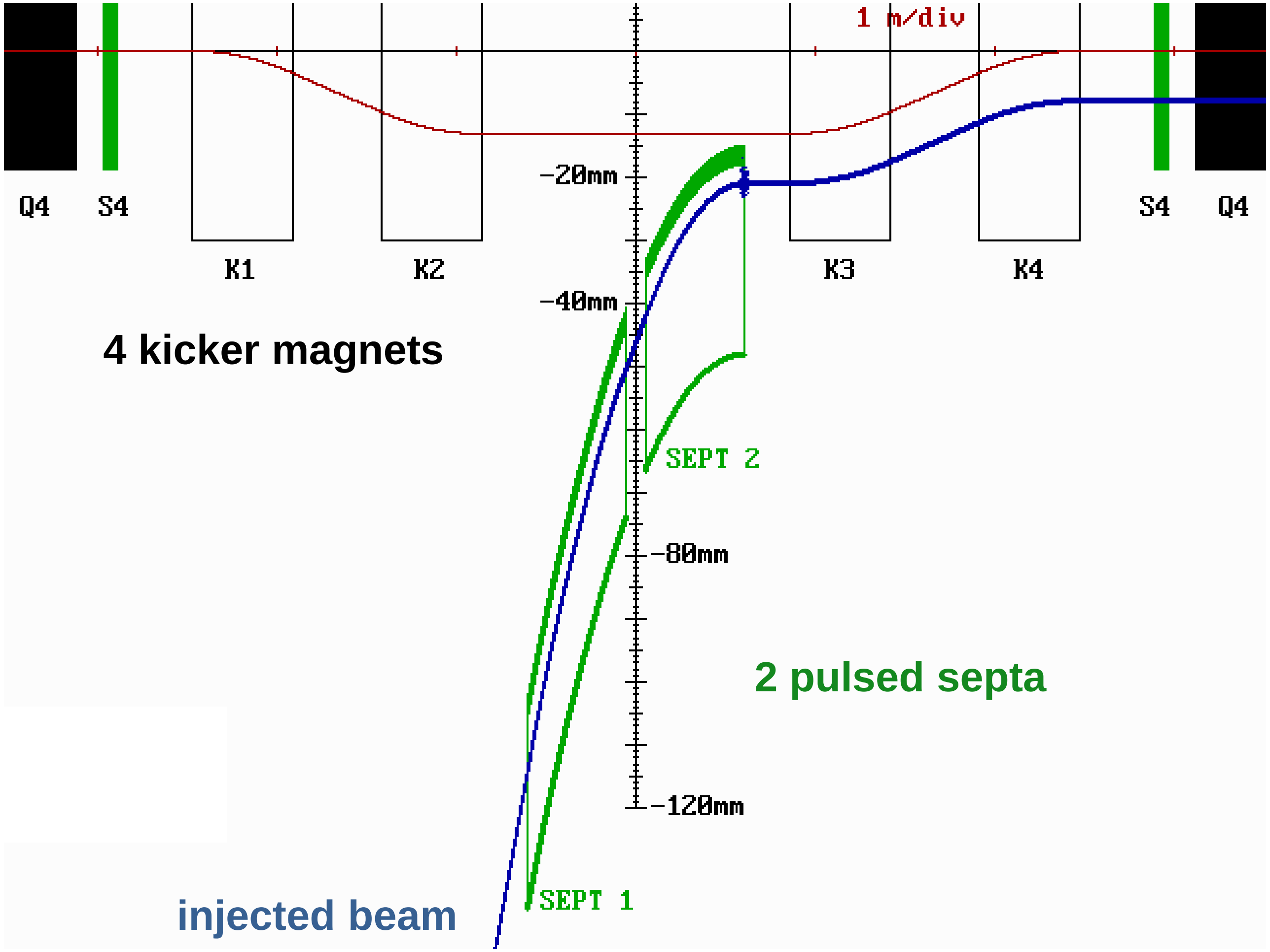
DC-Lambertson Septum, MAXIV, The MAX IV Detailed Design Report, http://www.maxlab.lu.se/maxlab/max4/DDR_public/index.html.

J. Borburgh, et al., "Final Results on the CERN PS Electrostatic Septa", Proceedings of PAC'03

"Massless septum" = non-linear kicker, T. Atkinson, et al., "Development of a Non-Linear Kicker System to Facilitate a new Injection Scheme for the BESSY Storage Ring", Proceedings of IPAC2011, San Sebastián, Spain

BESSY II parameters

stored beam

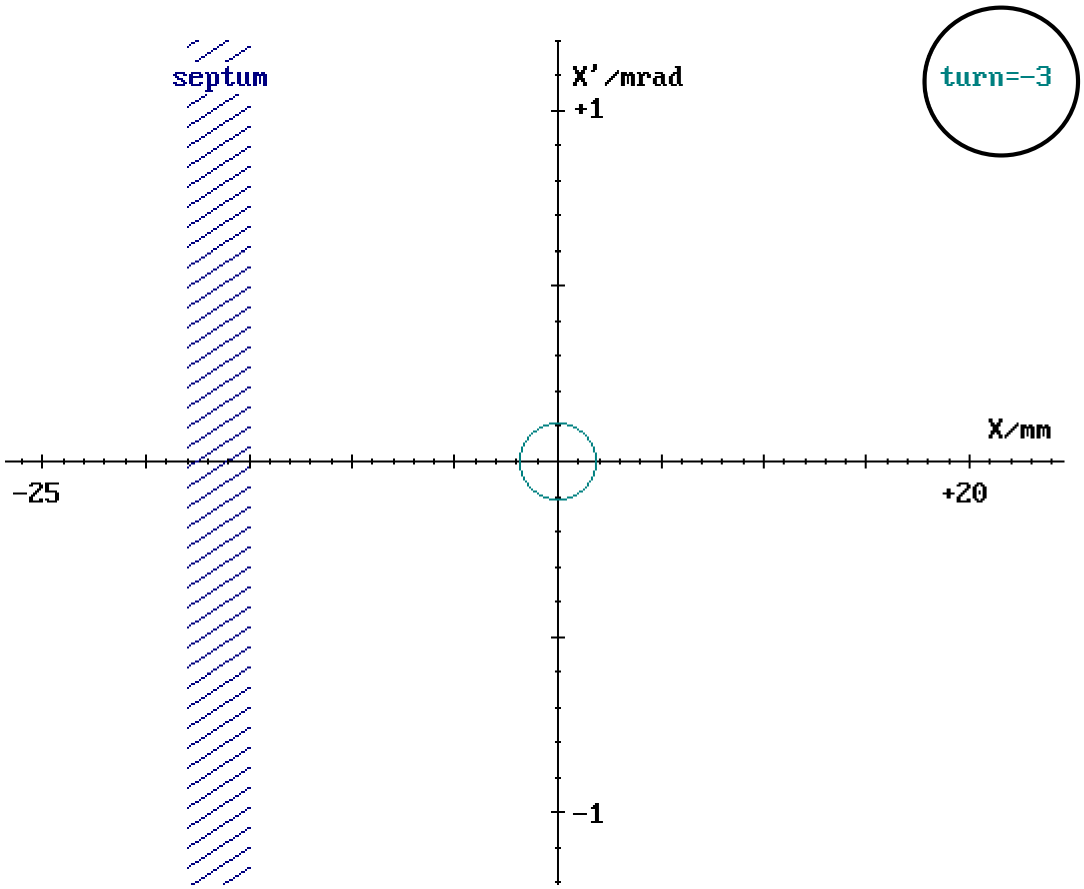


4 kicker magnets

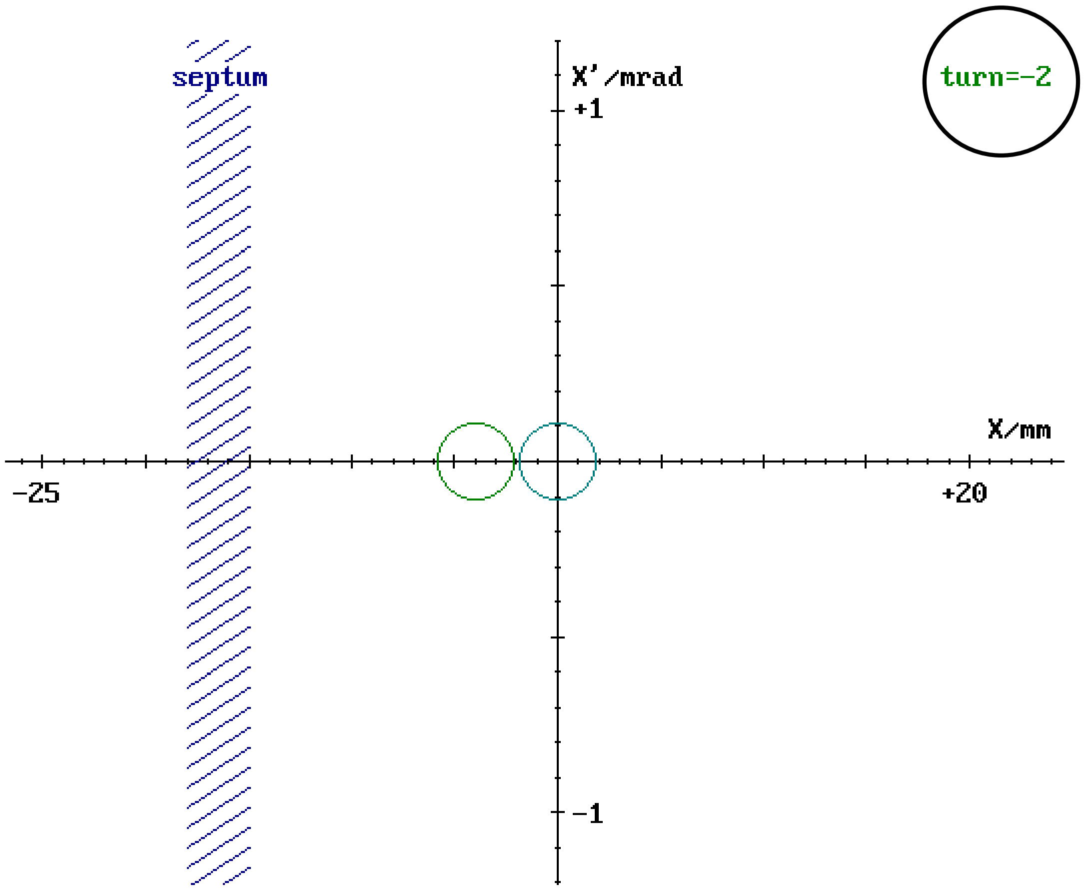
2 pulsed septa

injected beam

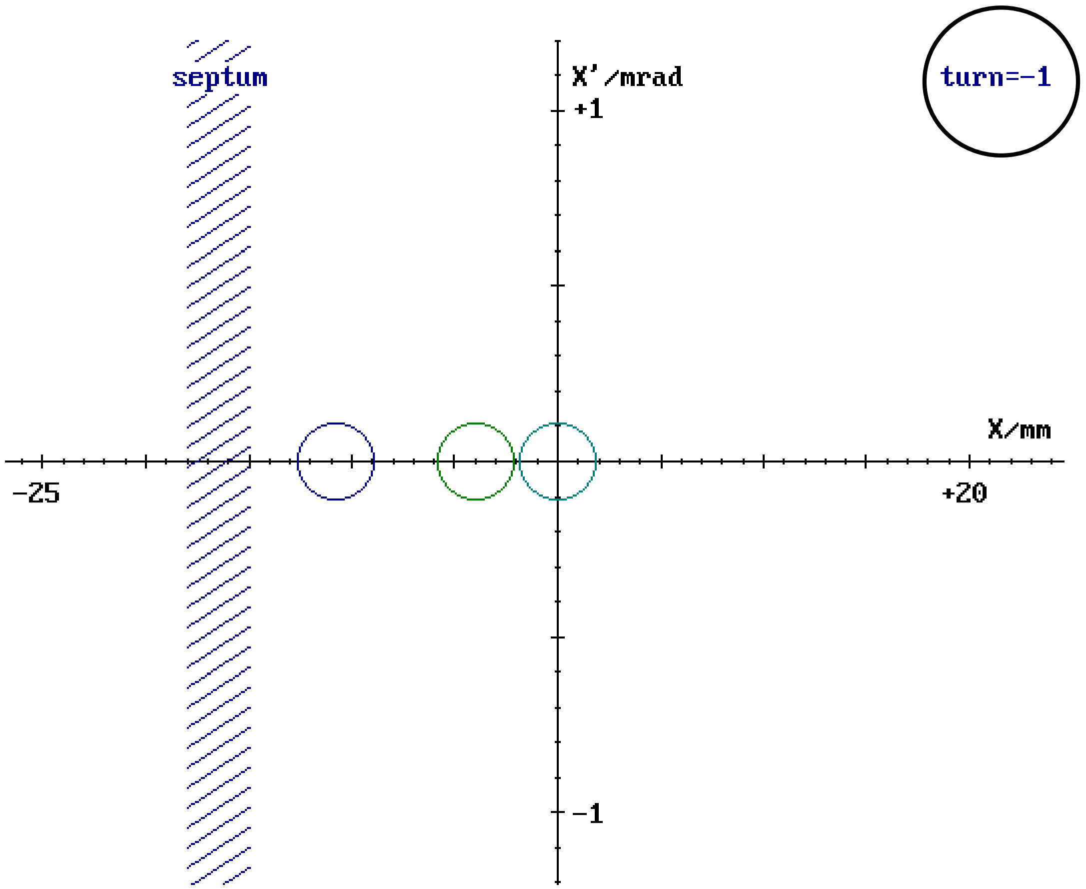
horizontal phase space



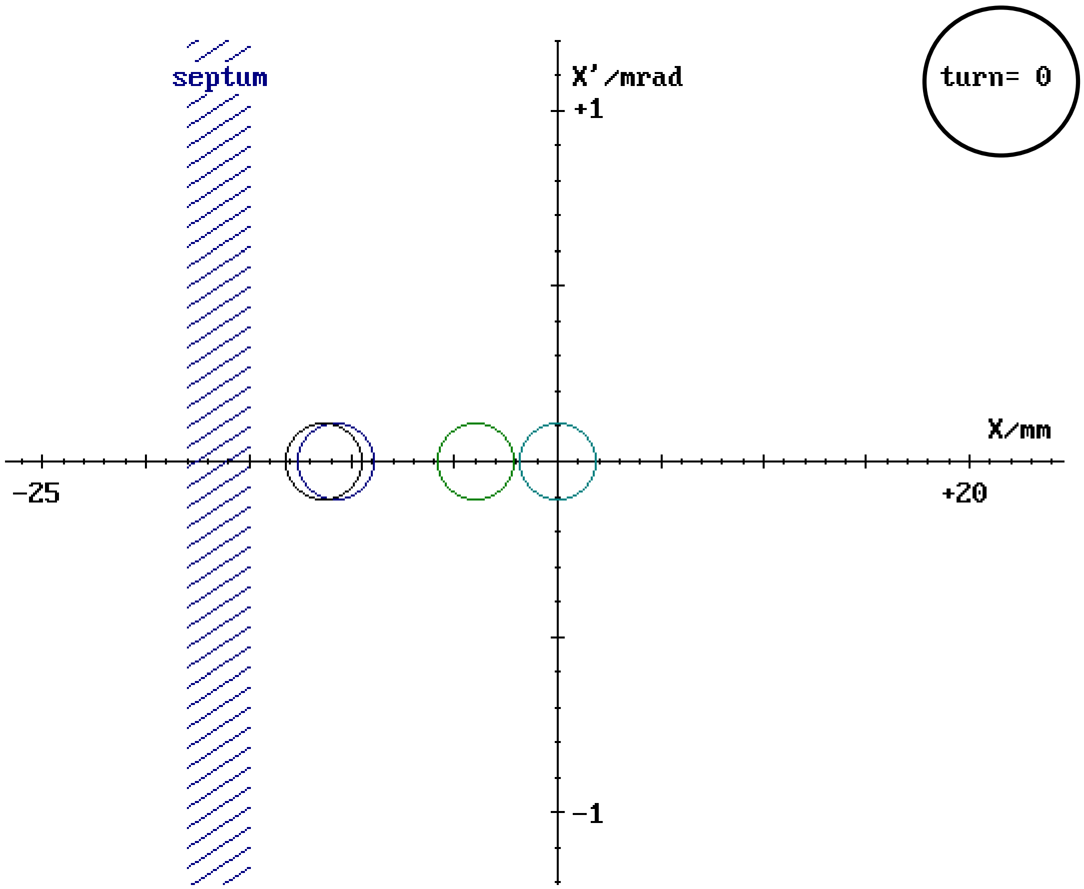
horizontal phase space



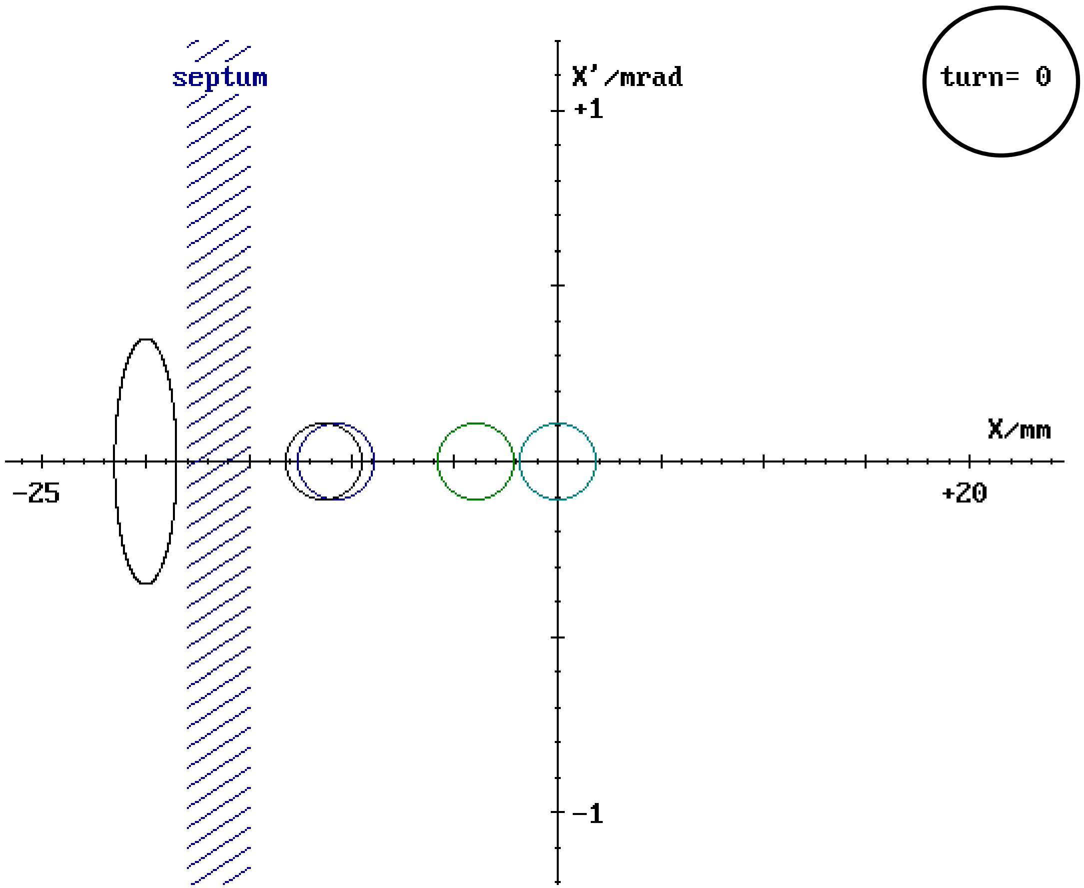
horizontal phase space



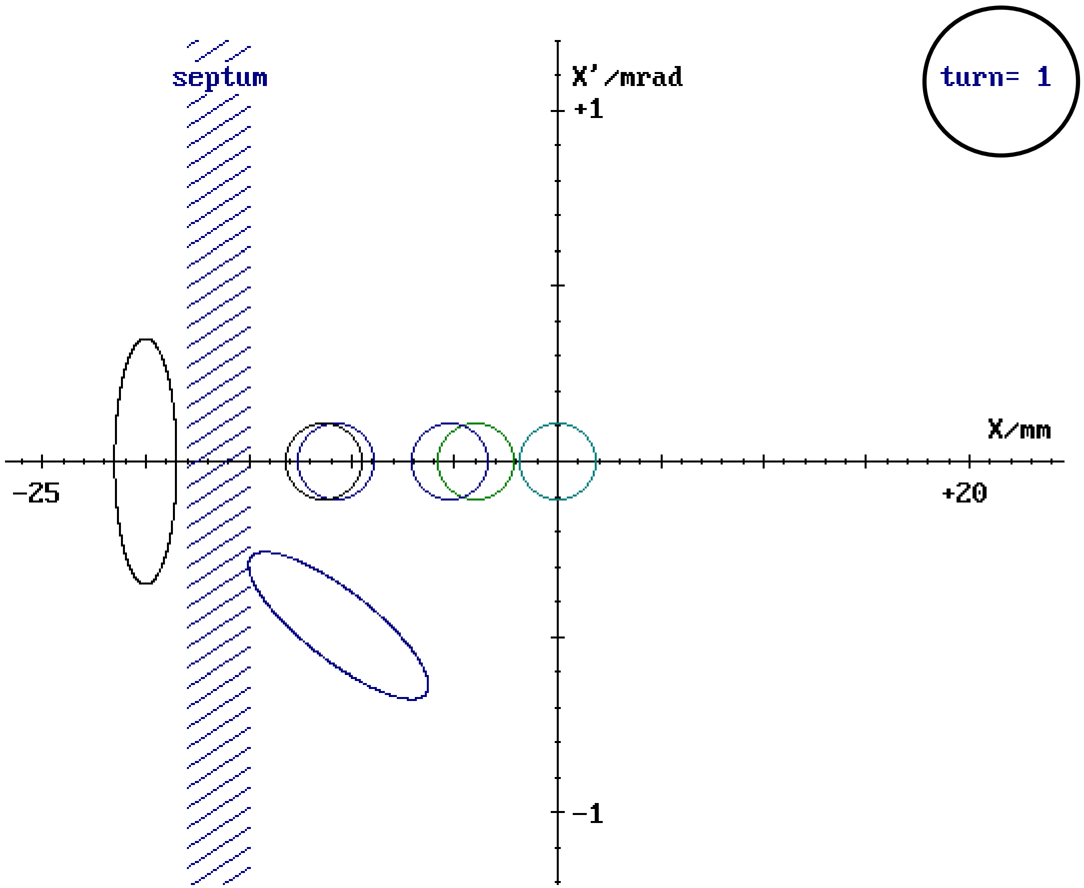
horizontal phase space



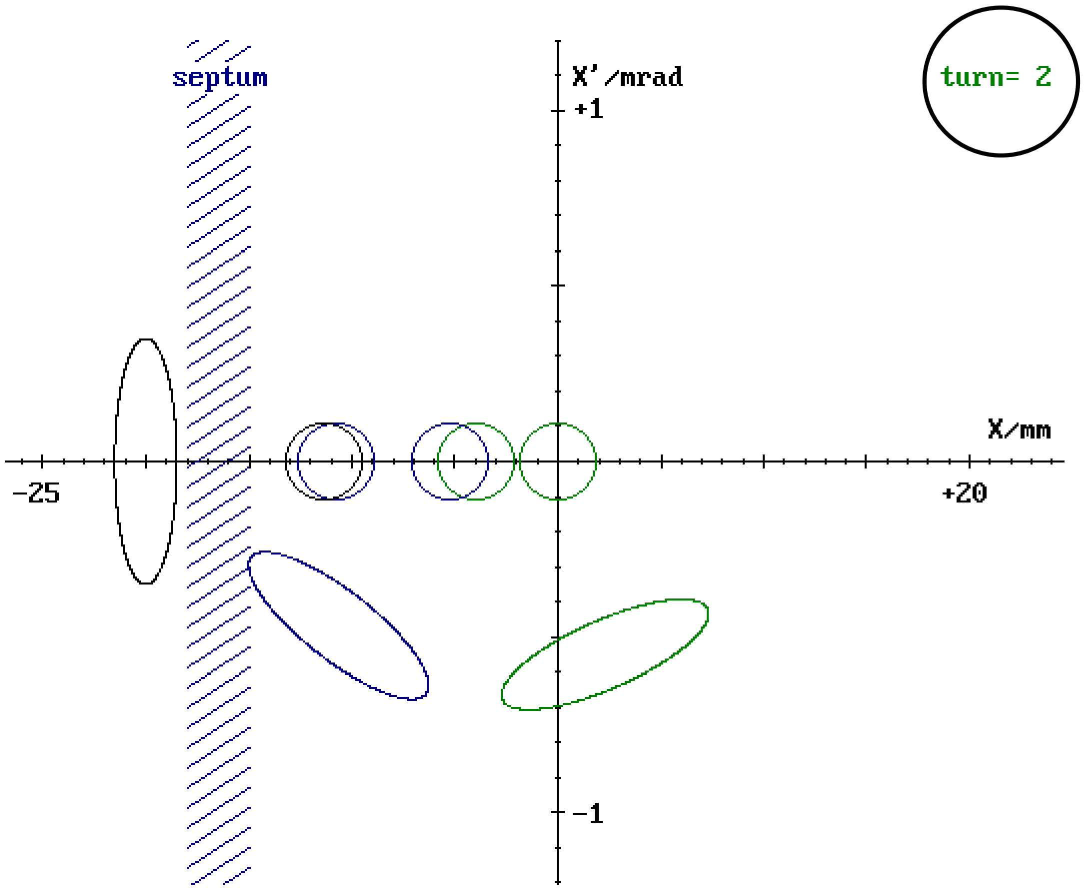
horizontal phase space



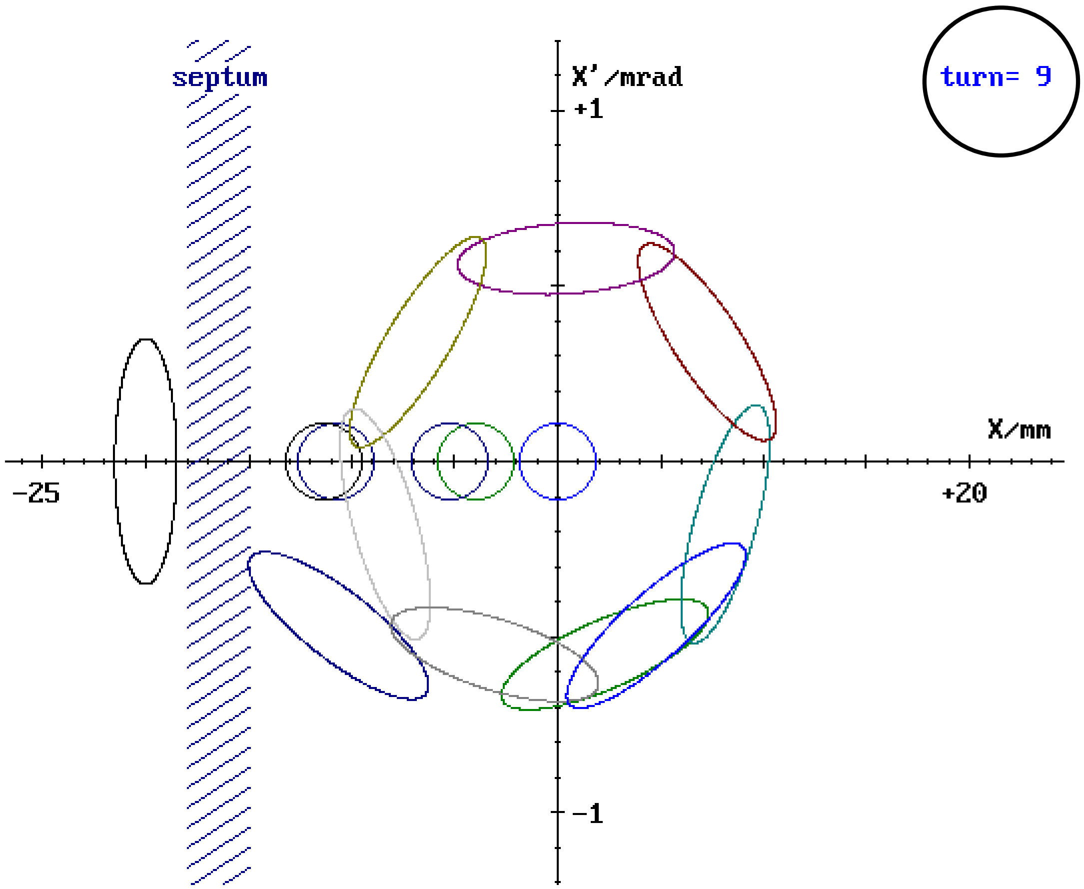
horizontal phase space



horizontal phase space

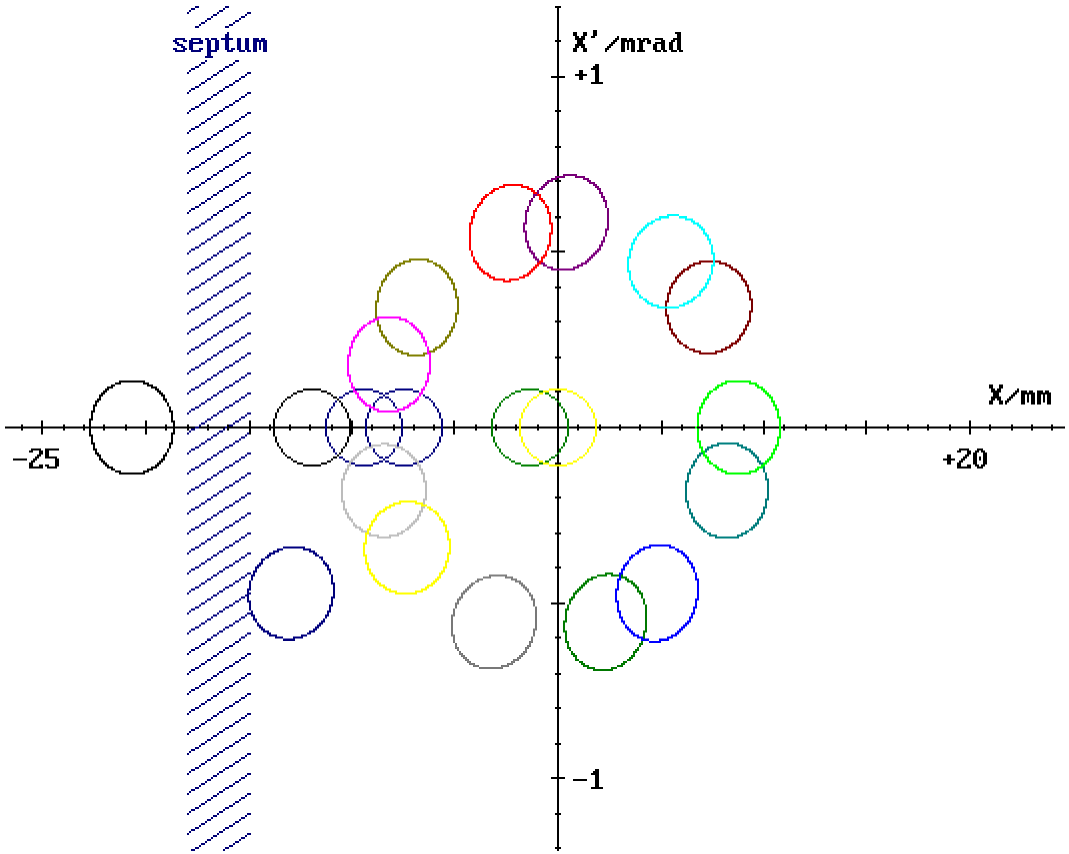


horizontal phase space



optimized injection parameter – aperture ~ 10.6 mm

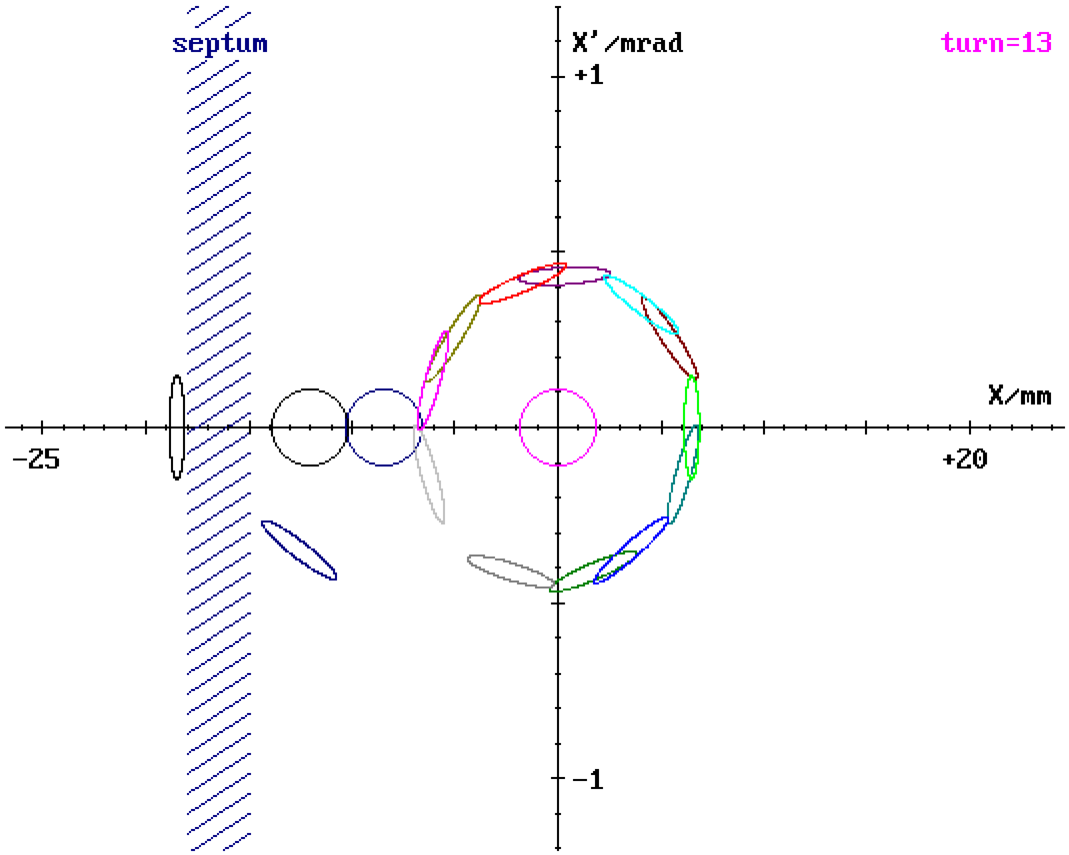
horizontal phase space



matched – $ß_{inj}$ = $ß_{sto}$, α_{inj}=α_{sto}=0 – aperture ~11.3 mm

II.1 Emittance Exchange and Optimized Injection Parameters

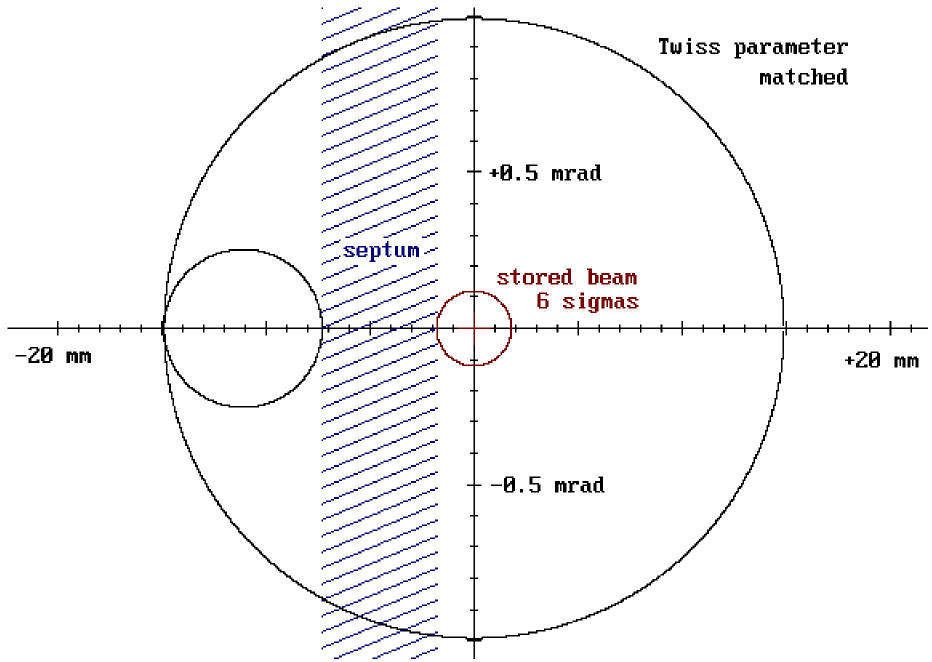
Emittance exchange: flat beam in synchrotron – either emittance sharing (on-coupling resonance) or full exchange – can significantly reduce horizontal emittance



Translates directly to much smaller needed dynamic aperture ~ 7 mm

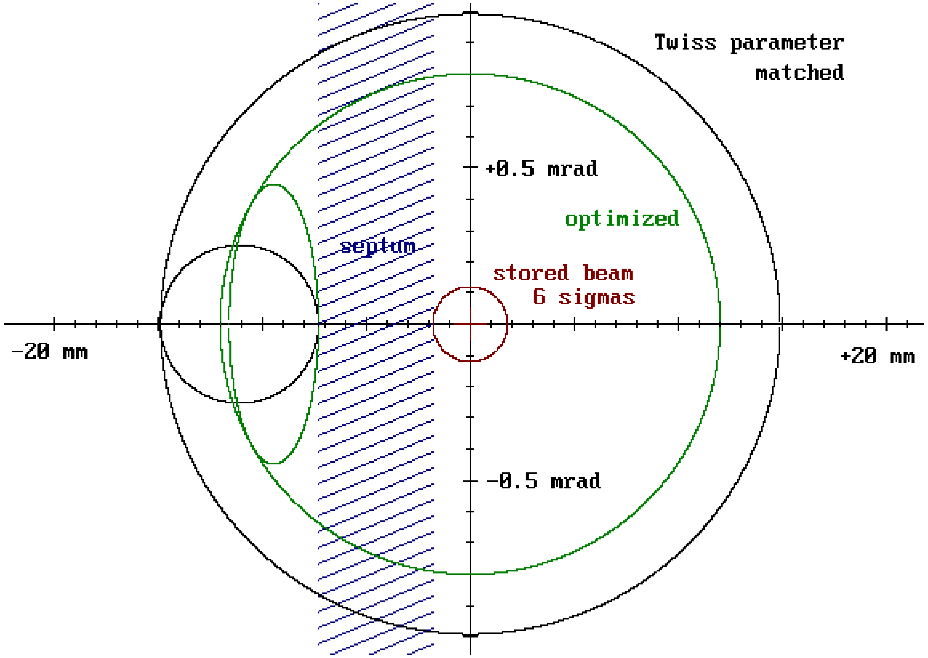
P. Kuske, F. Kramer, Transverse Emittance Exchange for Improved Injection Efficiency, proceedings of IPAC'16, WEOAA01

Matched – $ß_{inj} = ß_{sto}$, $\alpha_{inj}=\alpha_{sto}=0$



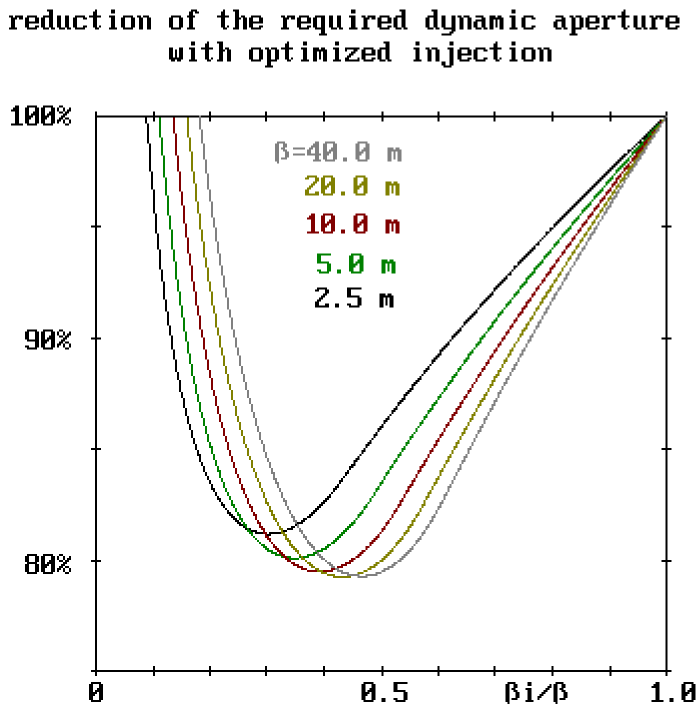
II.1 Optimized Injection Parameters

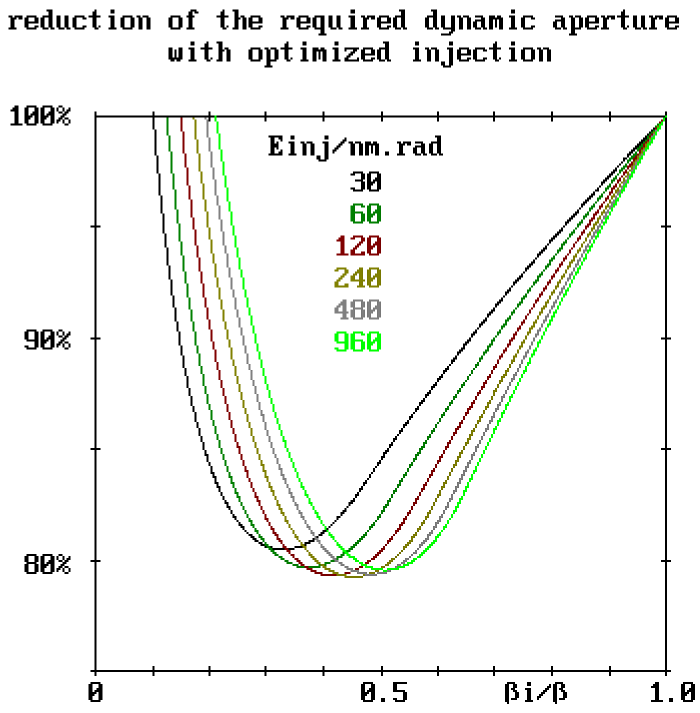
optimized – $\beta_{inj} < \beta_{sto}$, $\alpha_{inj}=\alpha_{sto}=0$



- **optimization works for most of the transverse injection schemes except the non-linear kicker**
- **with smaller and smaller emittance of stored and injected beam most of the valuable dynamic aperture eaten up be septum**

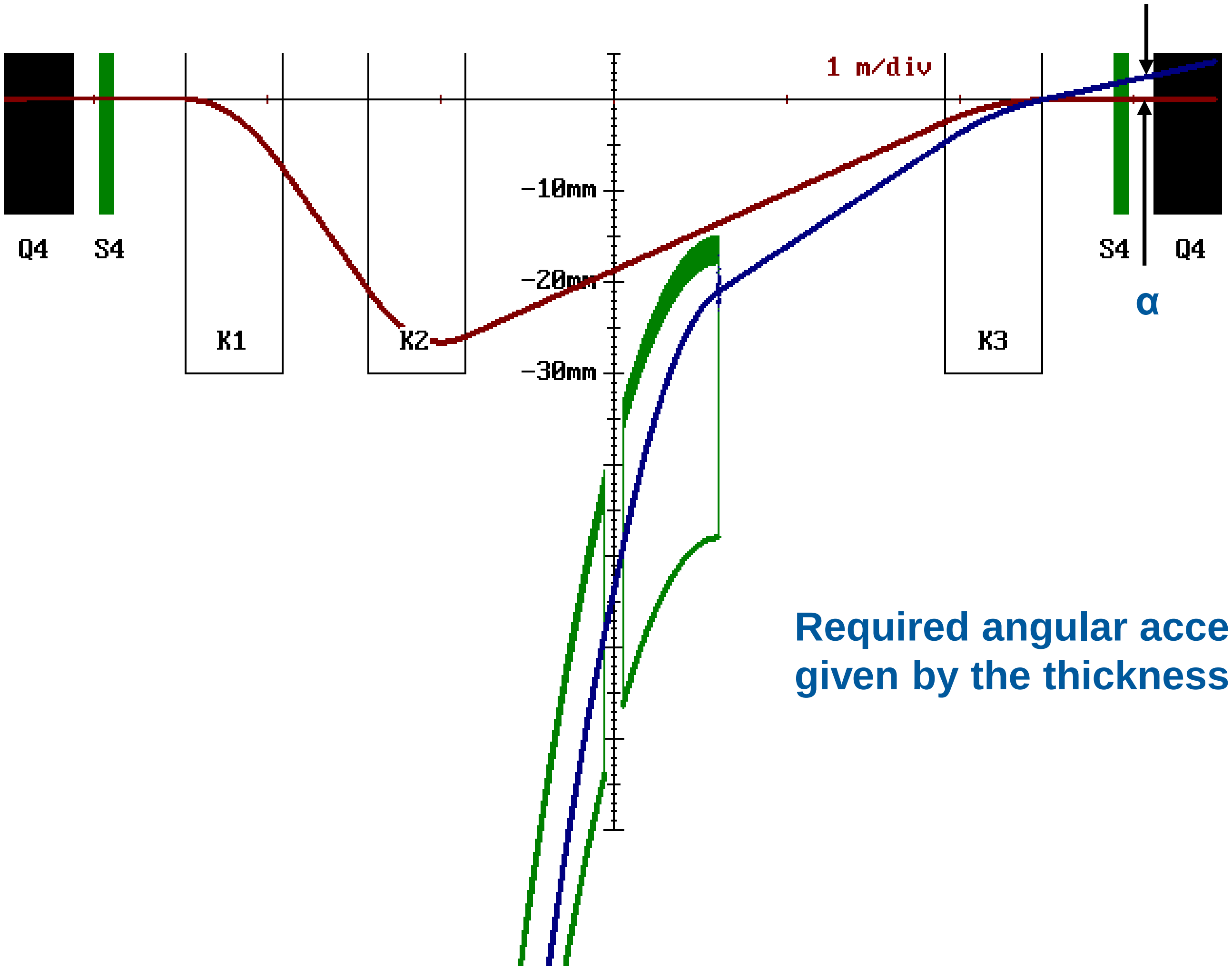
Smaller ß-values at the end of the transfer lines reduce required dynamic aperture by up to 20% - a gain of typically 2 mm





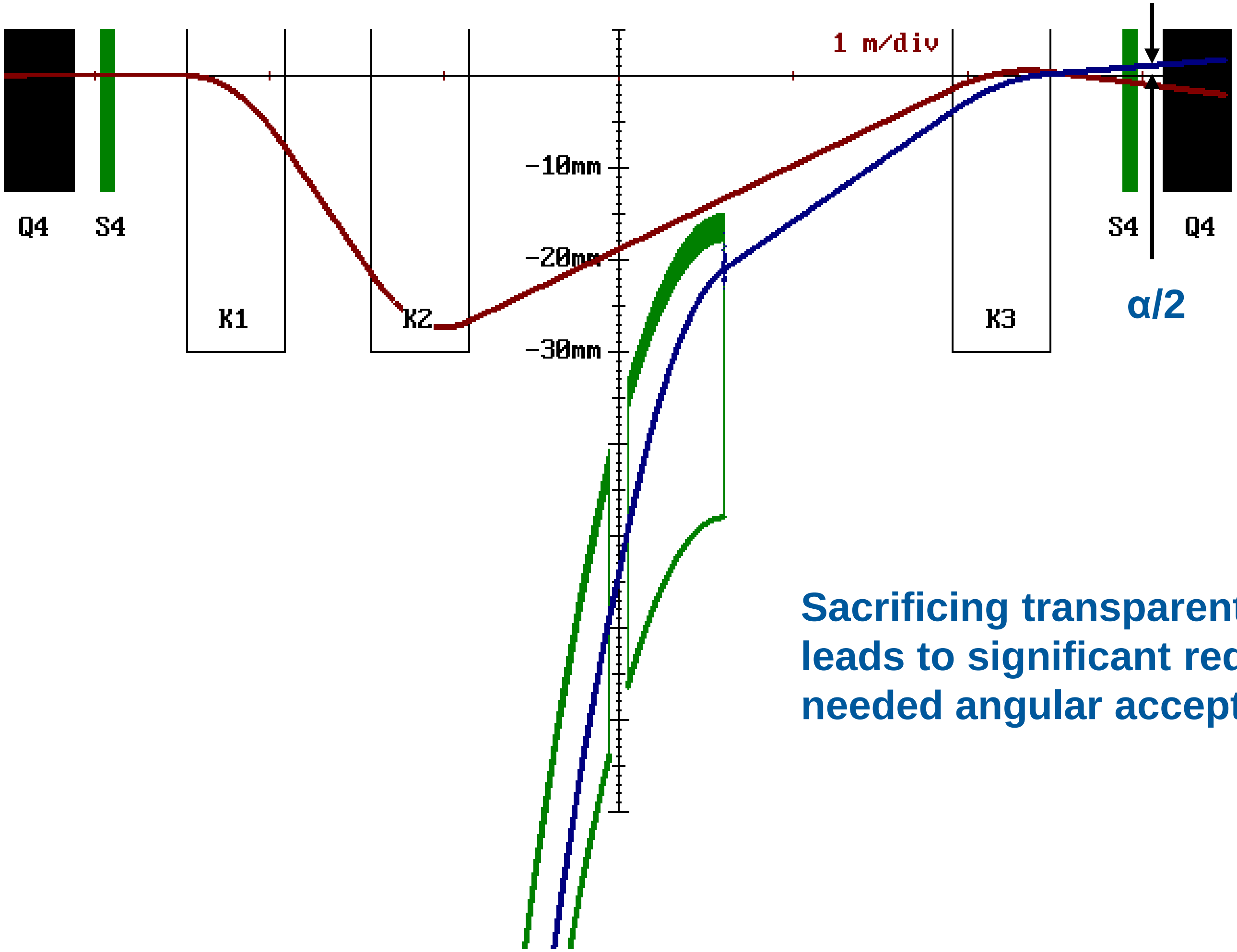
Andreas Streun, “SLS booster-to-ring transferline optics for optimum injection efficiency”, SLS-TME-TA-2002-0193, May, 2005

3 Kicker Bump – On-Axis, Off-Angle Injection

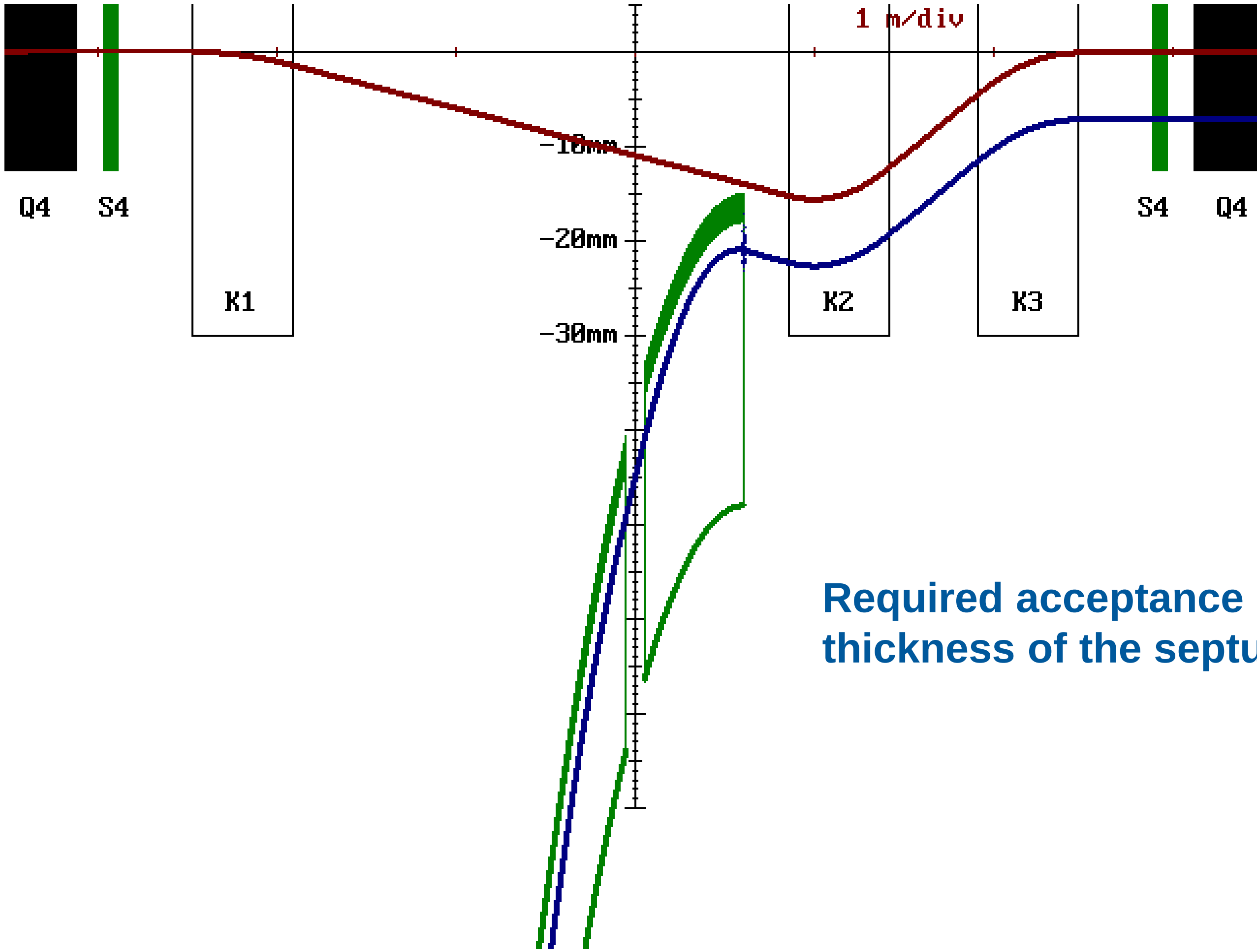


Required angular acceptance, α, given by the thickness of the septum

III. 3 Kicker Bump – On-Axis, Off-Angle Injection

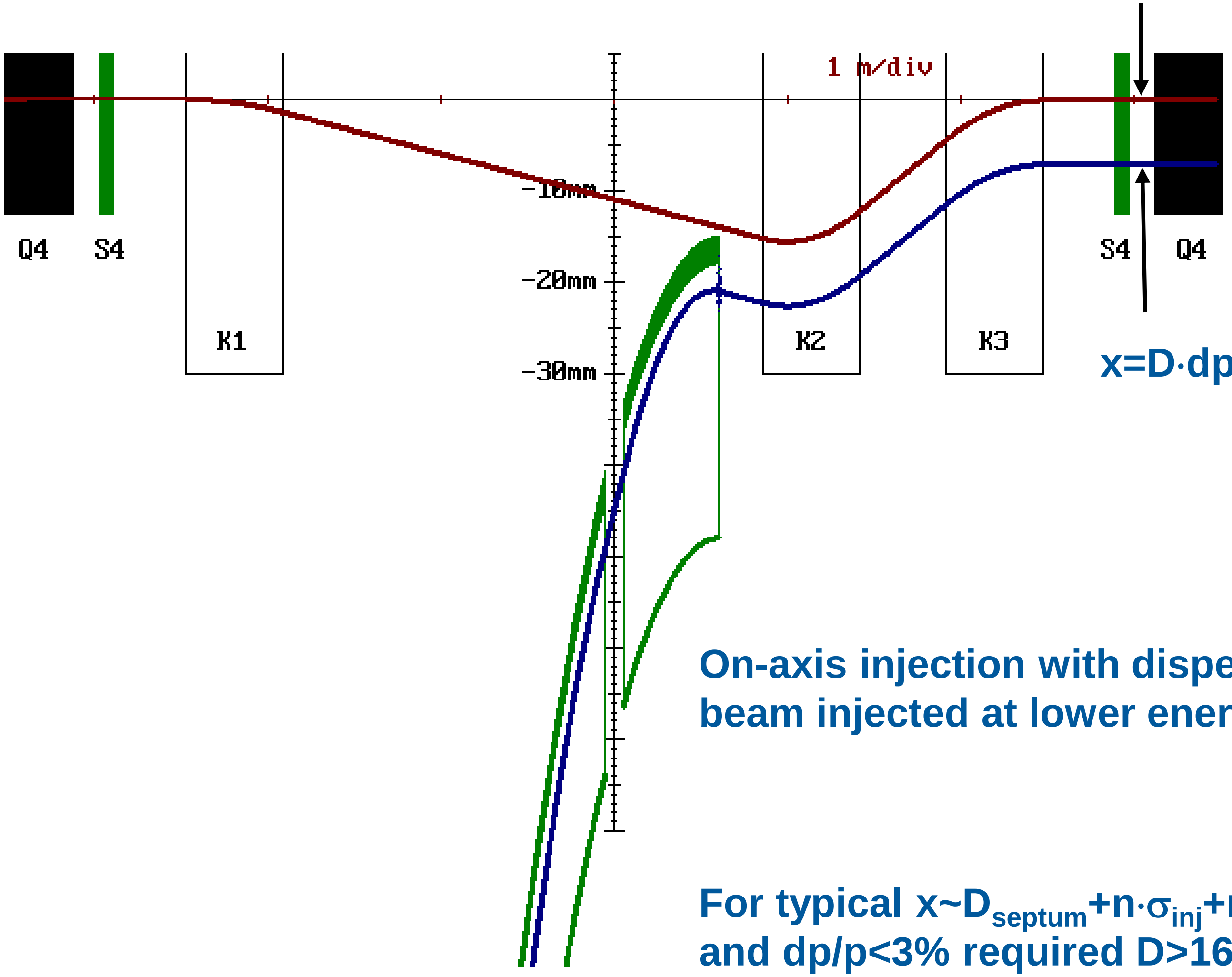


Sacrificing transparent injection leads to significant reduction in needed angular acceptance (APS).



Required acceptance given by the thickness of the septum

III.1 3 Kicker Bump – On-Axis, Off-Momentum Injection



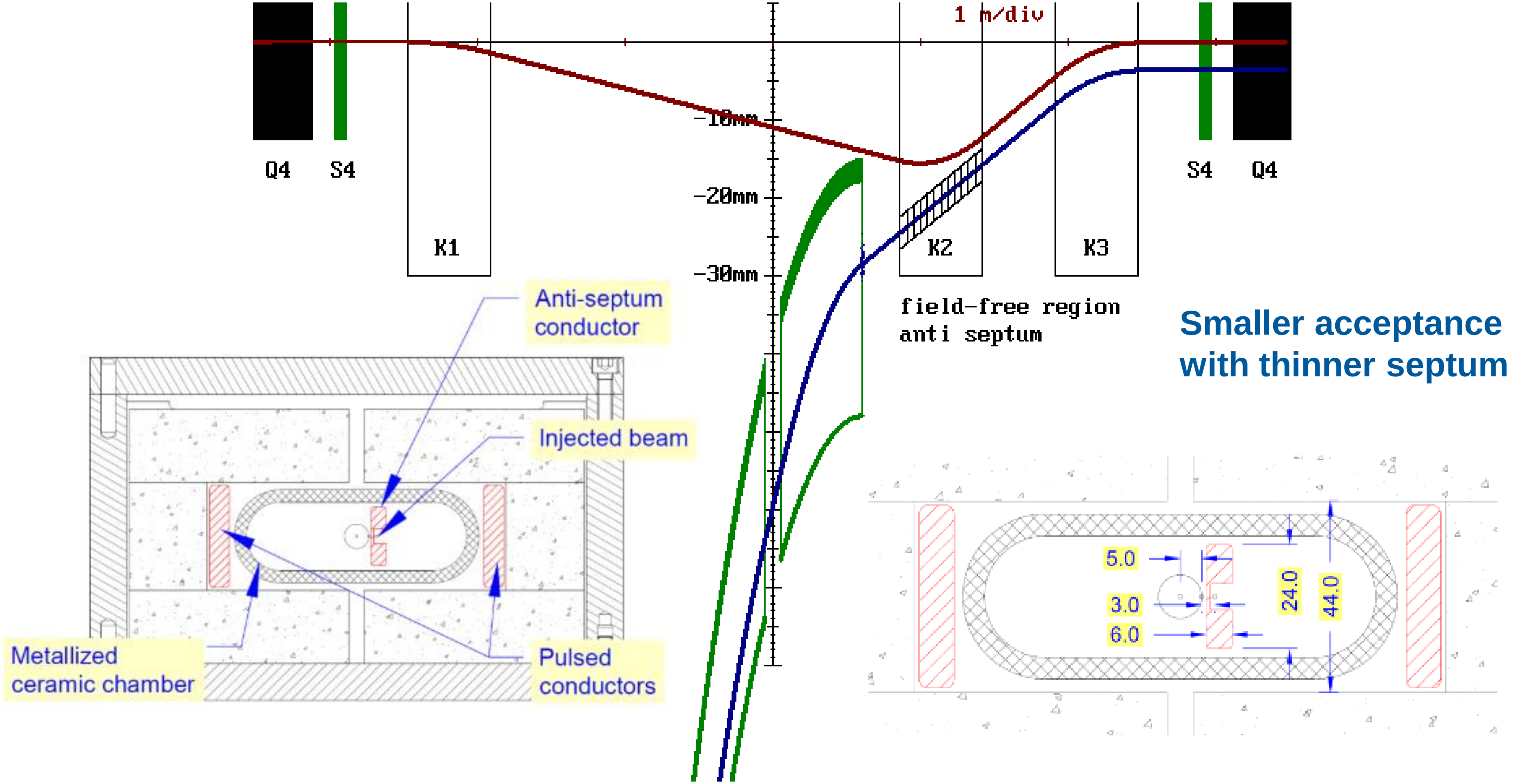
x=D·dp/p

On-axis injection with dispersion, D, and beam injected at lower energy, dp/p < 0

For typical $x \sim D_{septum} + n \cdot \sigma_{inj} + m \cdot \sigma_{st} \sim 5mm$ and dp/p<3% required D>16cm – too large for any low emittance ring

P. Collier, "Synchrotron Phase Space Injection Into LEP", Proceedings of PAC'95

III.2 3 Kicker Bump – Off-Axis Injection with Anti Septum

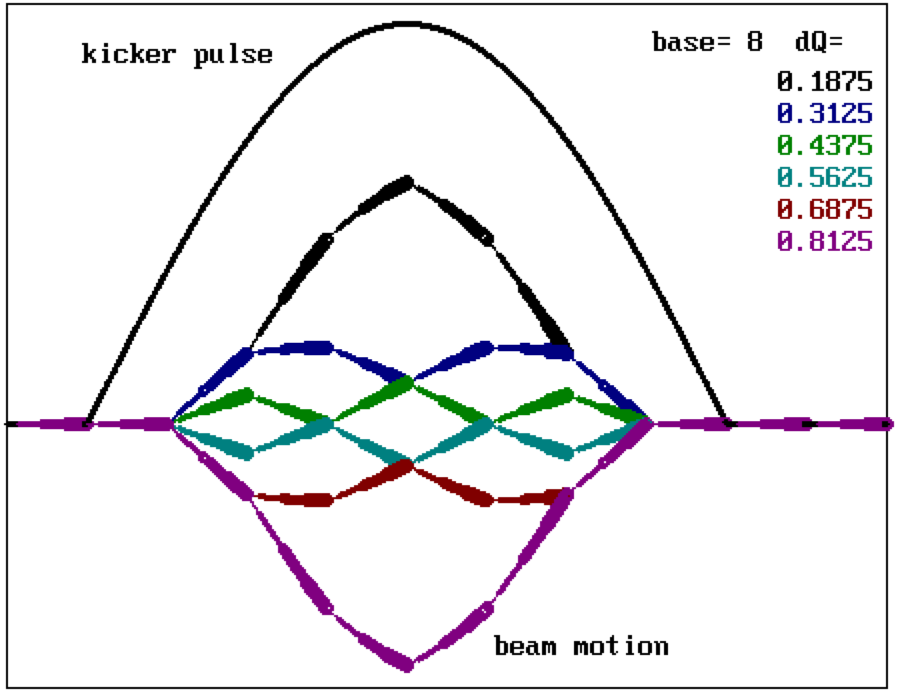


Smaller acceptance with thinner septum

C. Gough, et al., Injection into Small Aperture Rings using an "Antiseptum", contribution to the Topical Workshop on Injection and Injection Systems, 28-30 August 2017, Berlin, *https://indico.cern.ch/event/635514/*

A.V. Bondarenko, et al., "A New Beam Extraction Scheme from a Synchrotron Using a Magnetic Shield", proceedings of RuPAC'08, Zvenigorod,Russia

Perfect closure of the injection bump is hard to achieve. In small rings the half-wave sinusoidal kicker pulse with a width at the base (number of turns: base>=4) will not create any long lasting orbit oscillations for special tunes: *dQ=(1.5+i)/base* with *i*=0…*base*-3



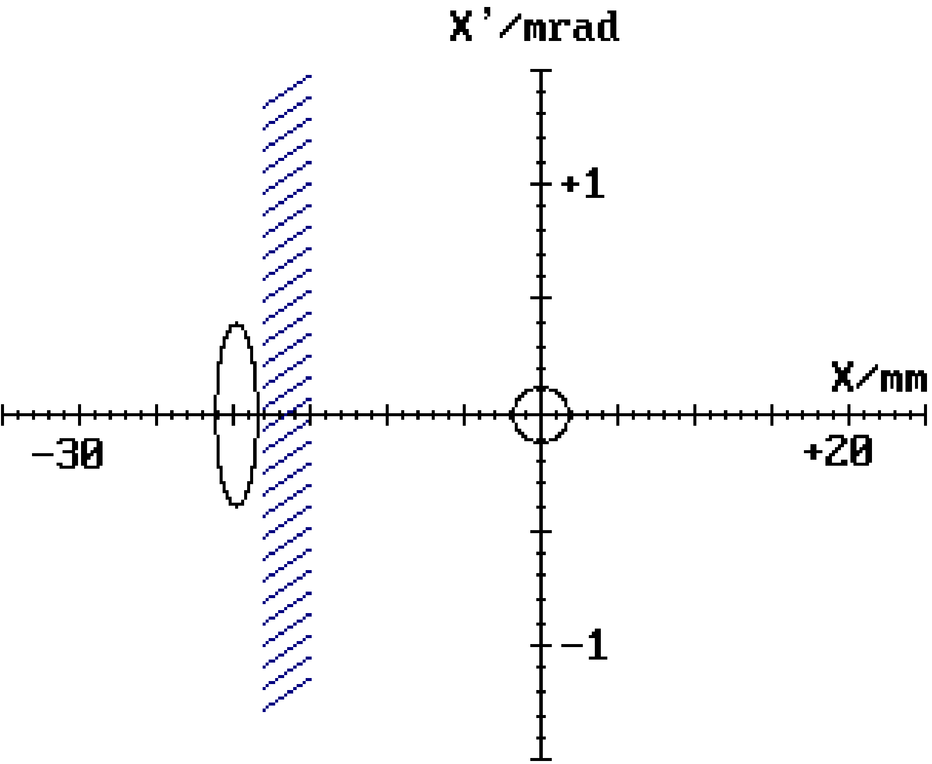
If tune and the length of your kicker pulses (and the shape) can be chosen according to this equation the bump would be closed after the kicker pulse.

C. Gough, et al., Injection into Small Aperture Rings using an "Antiseptum", contribution to the Topical Workshop on Injection and Injection Systems, 28-30 August 2017, Berlin, *https://indico.cern.ch/event/635514/*

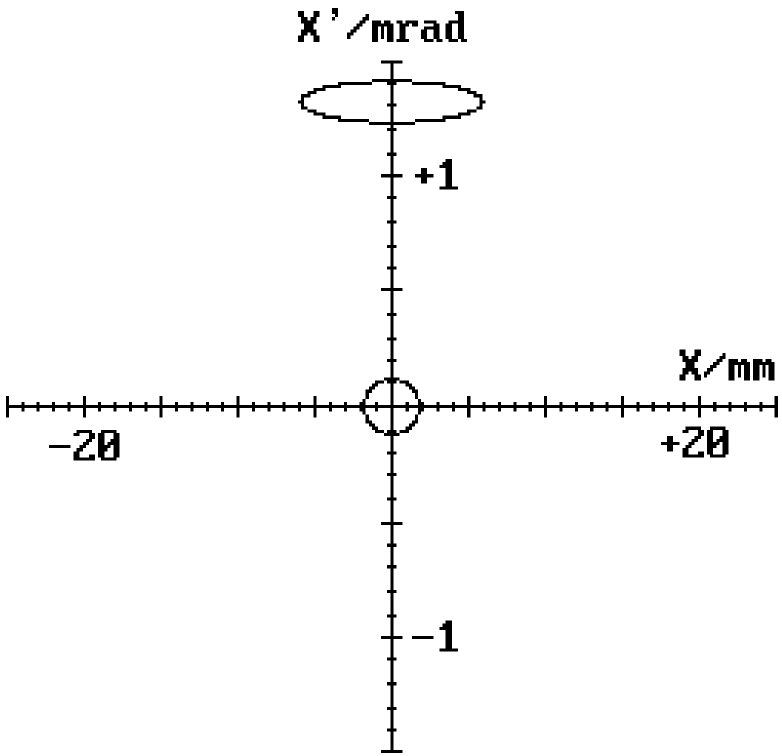
IV. Single Kicker Injection

used initially in MAXIV and in nearly all our booster synchrotrons

after phase advance of (n+0.25)·2π

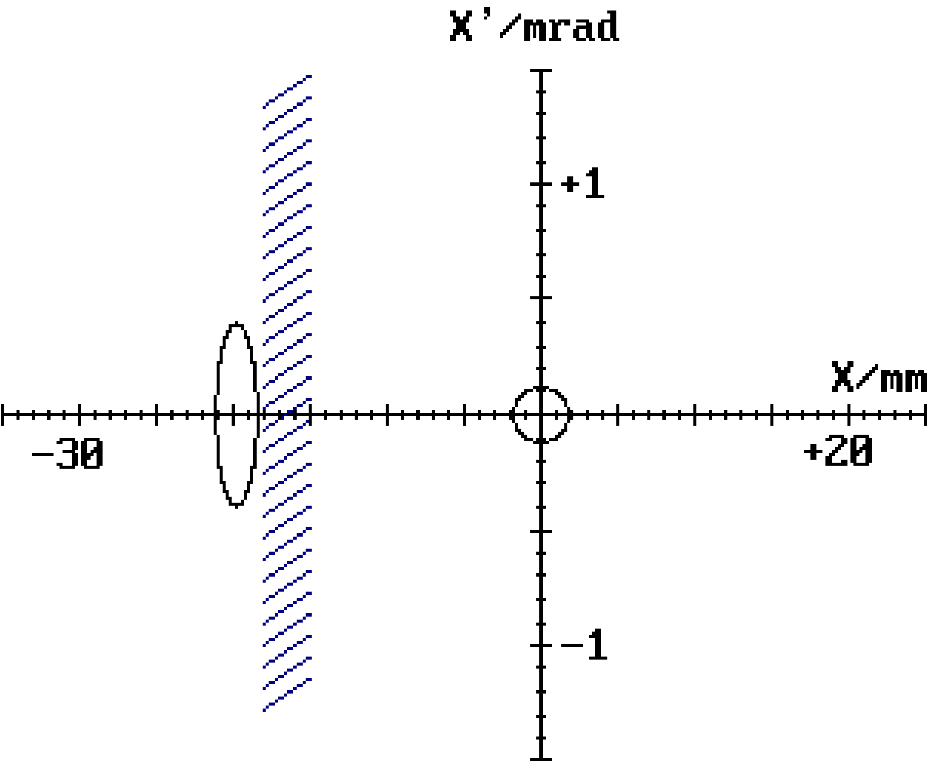


at the injection septum

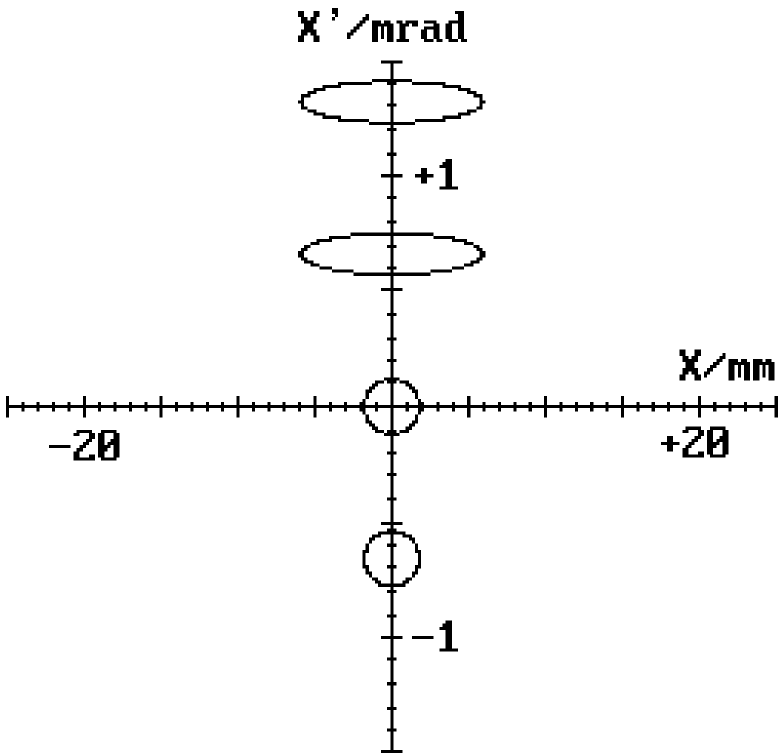


at the kicker

after phase advance of (n+0.25)·2π

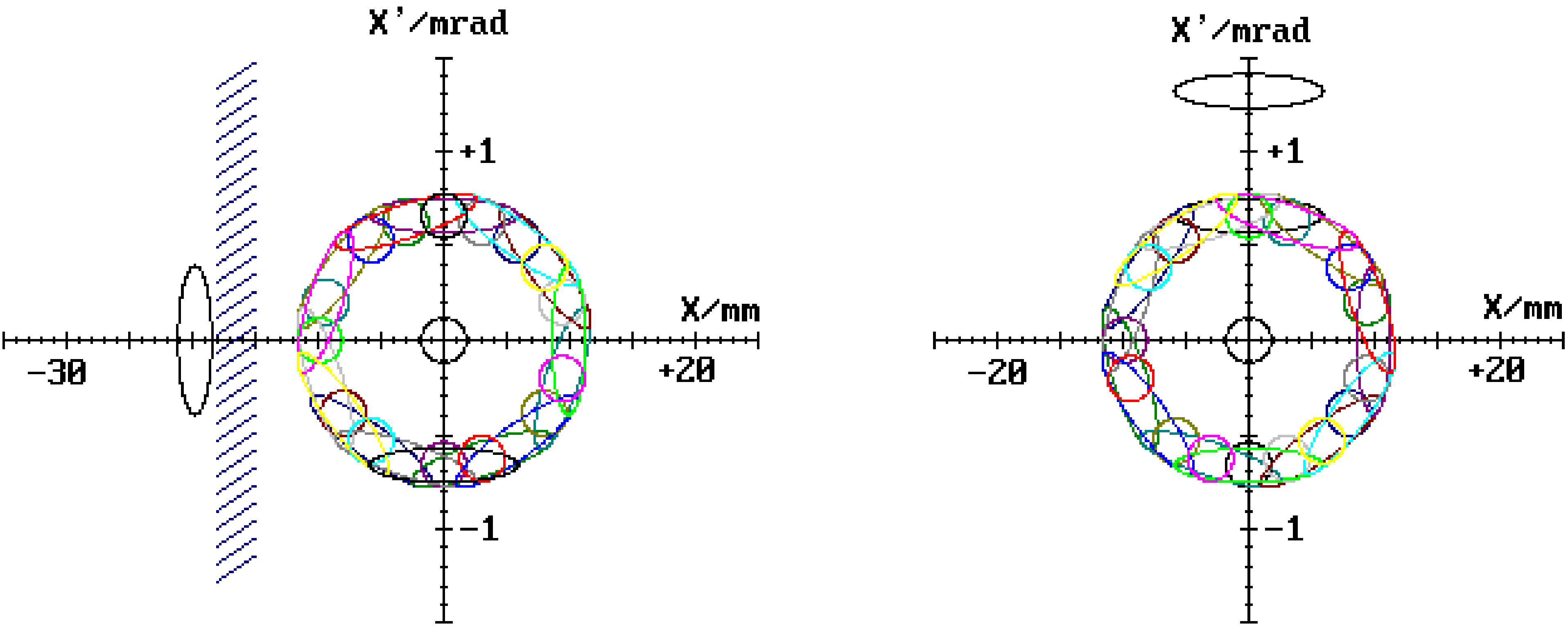


at the injection septum



at the kicker

injection kicker reduces momentum of the injected and creates momentum of the stored beam



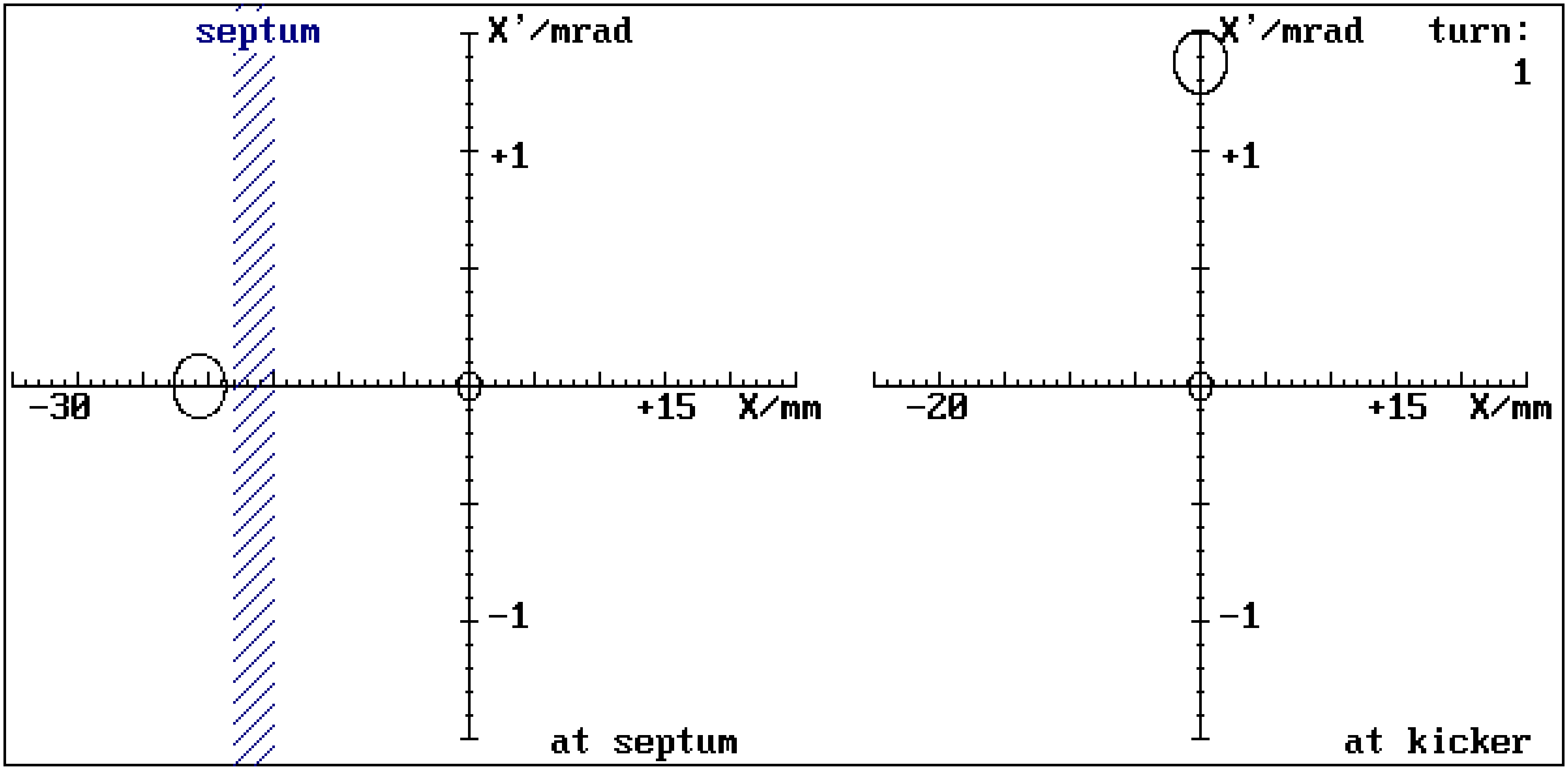
at the injection septum

at the kicker

both beams survive oscillating inside the acceptance of the ring – with fast stripline kicker only the topped-up bunch would be excited

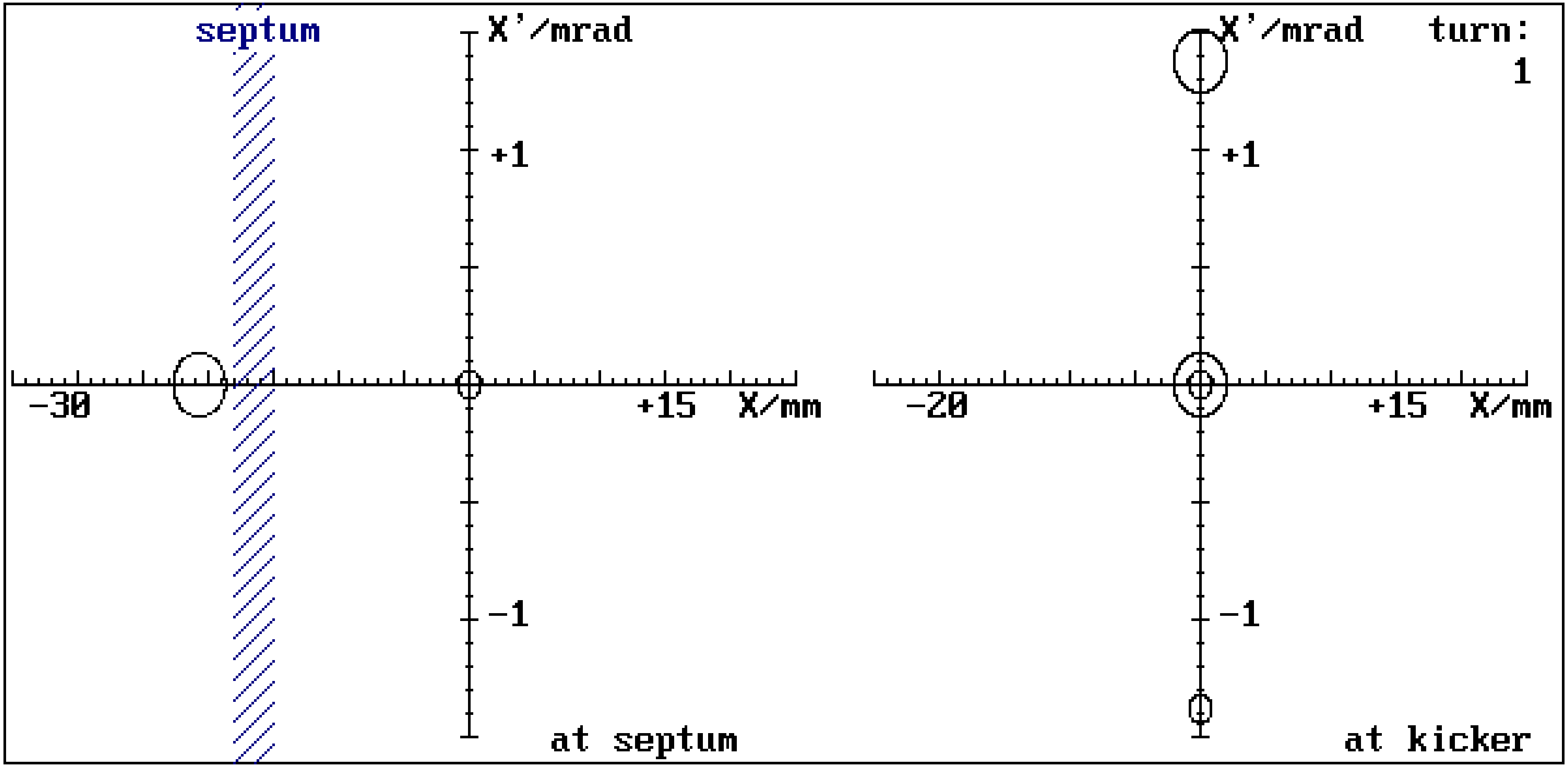
approach favoured by upgrade projects for APS and ALS

after phase advance of (n+0.25)·2π



approach favoured by upgrade projects for APS and ALS

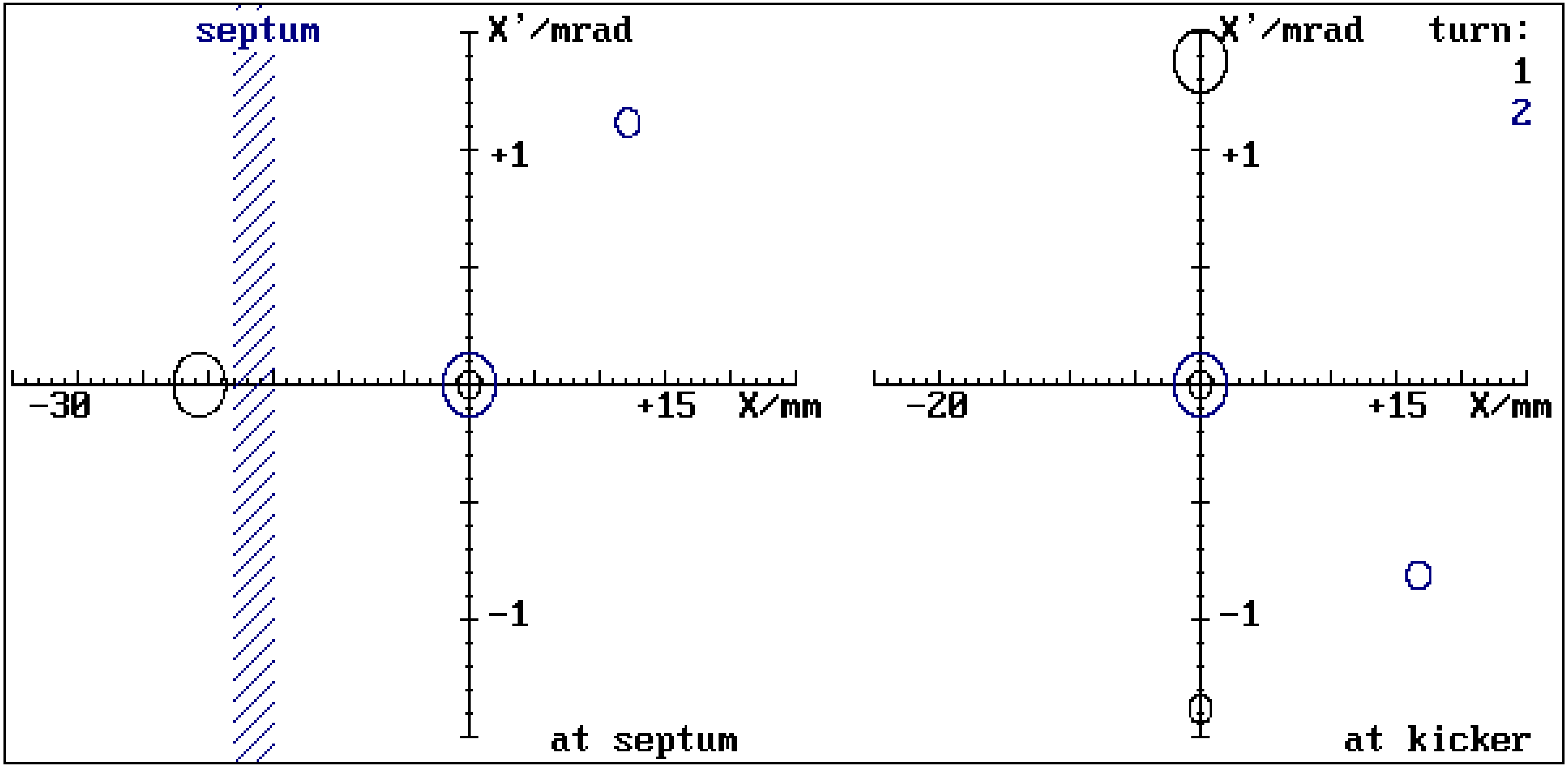
twice the kick strength required
to bring injected beam on-axis



V. Single Kicker Injection Swap-Out Injection

approach favoured by upgrade projects for APS and ALS

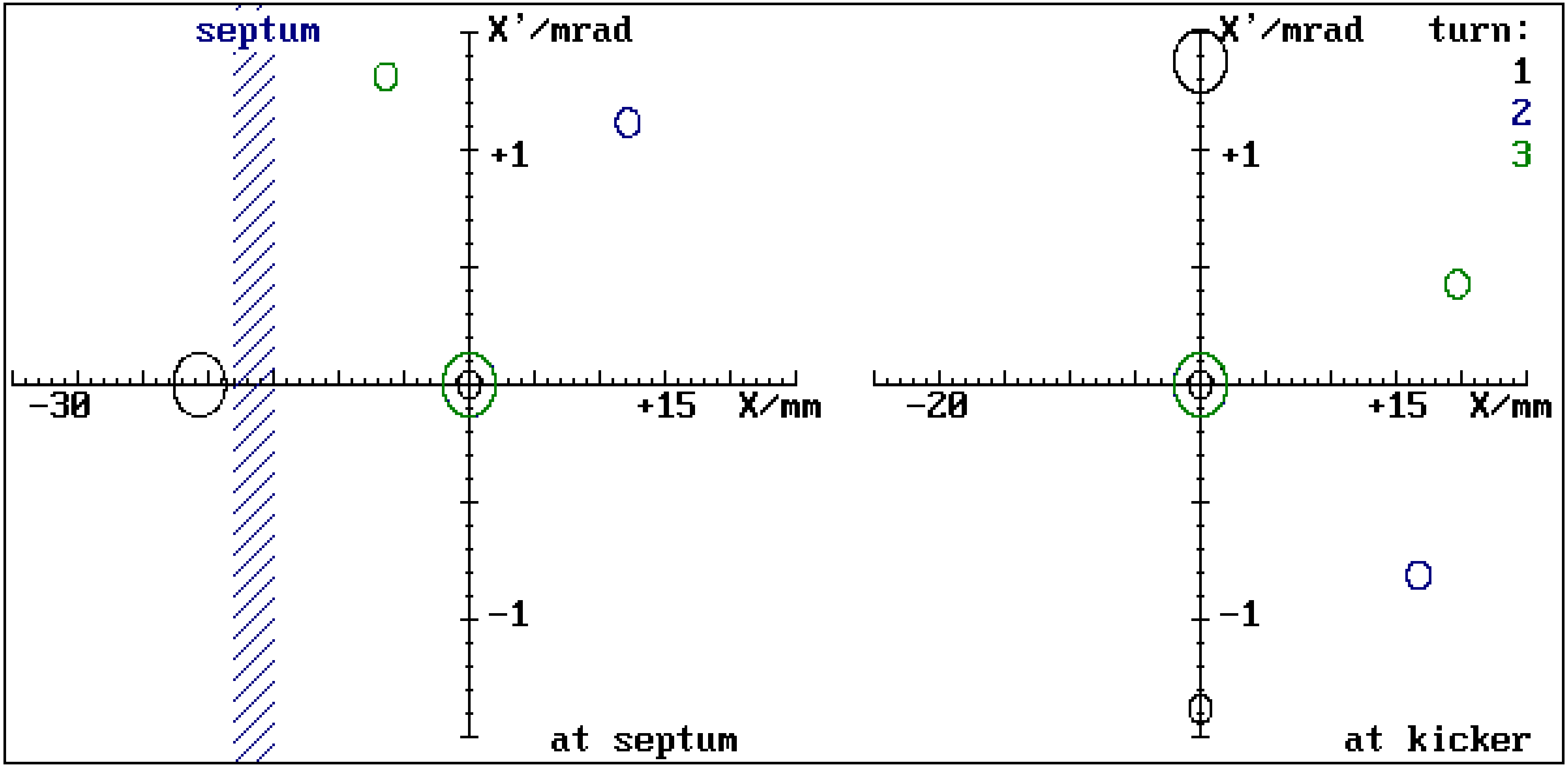
injected beam replaces old beam



V. Single Kicker Injection Swap-Out Injection

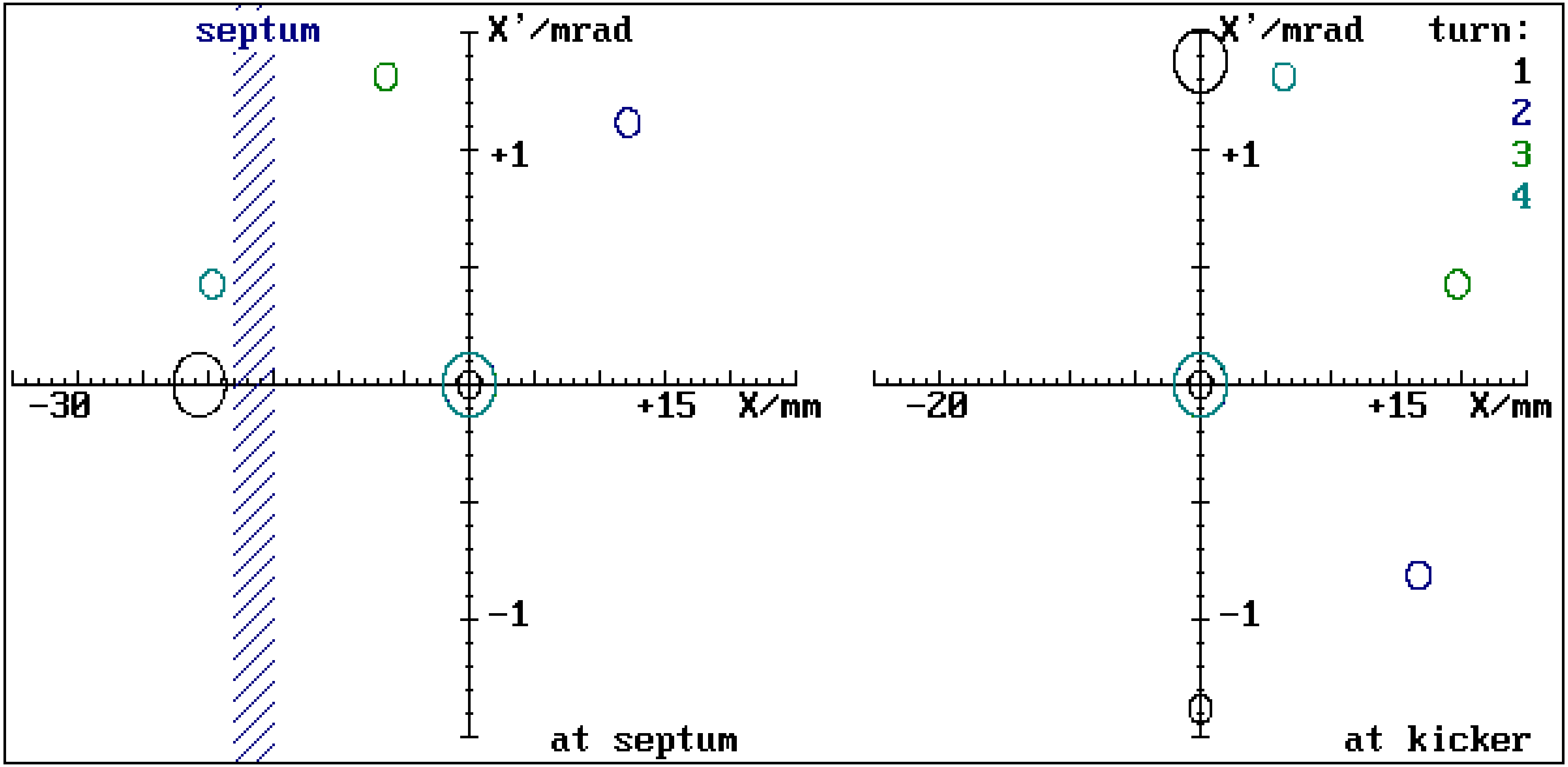
approach favoured by upgrade projects for APS and ALS

old beam circulates with large amplitude and is either dumped (APS, requiring a high accelerated charge) or recaptured in an accumulator ring (ALS)

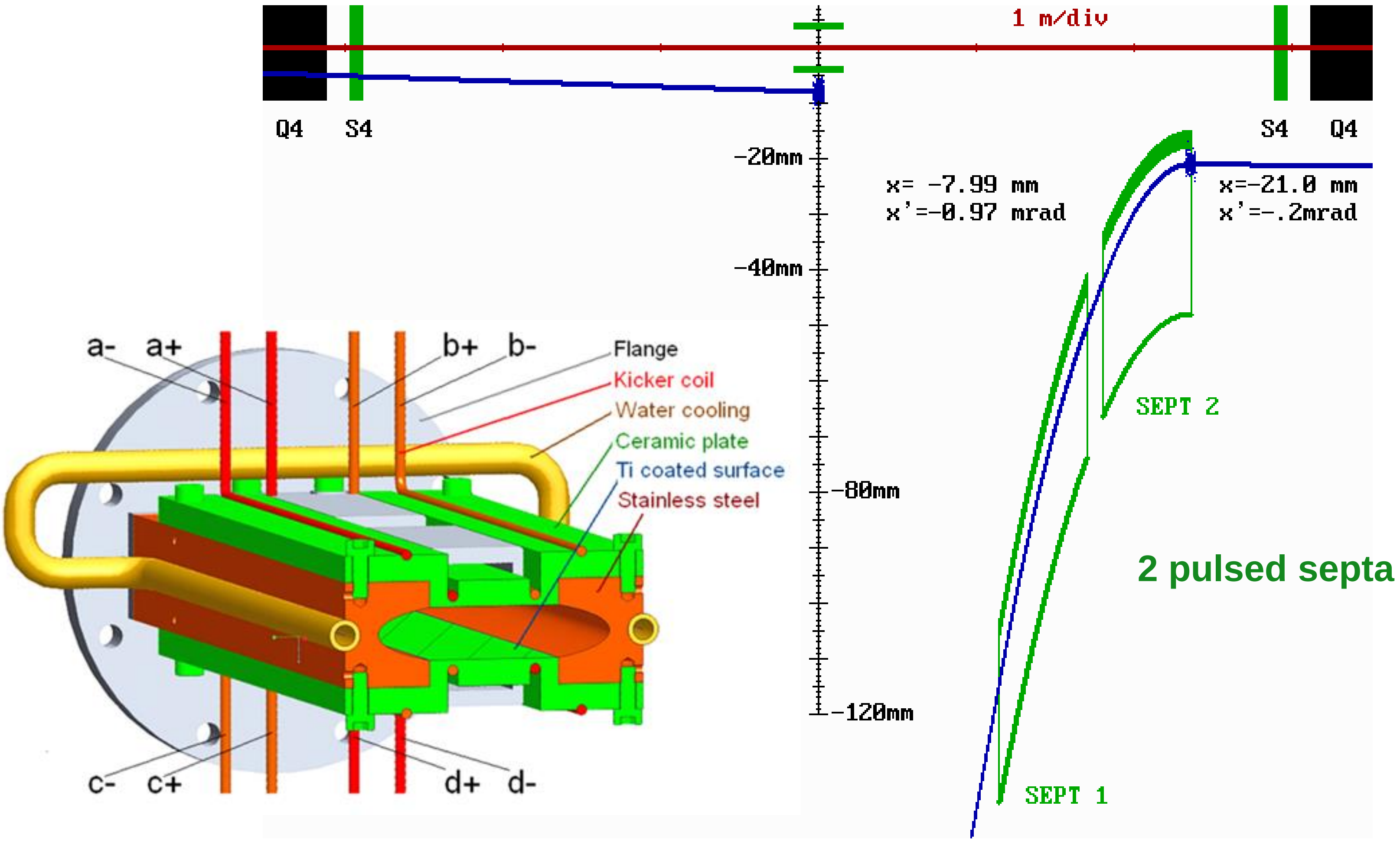


V. Single Kicker Injection Swap-Out Injection

At BESSY II the diagnostics kicker is located at an appropriate phase advance to perform on-axis, swap-out injections and old beam is lost at the septum after 3 turns

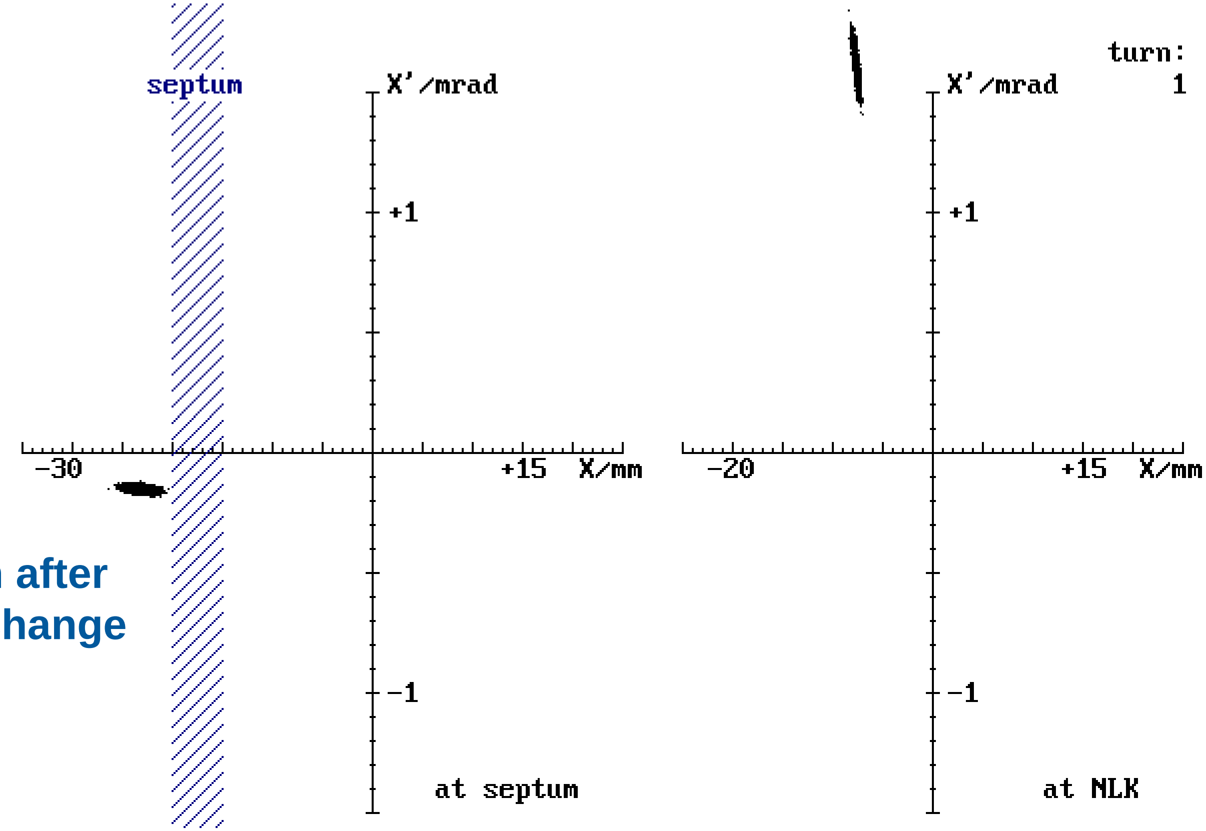


Proposed scheme for BESSY II, similar approach taken at MAXIV, SOLEIL, and SIRIUS



K. Harada, et al, New Injection Scheme Using a Pulsed Quadrupole Magnet in Electron Storage Rings, Phys. Rev. ST-AB 10, 123501, 2007

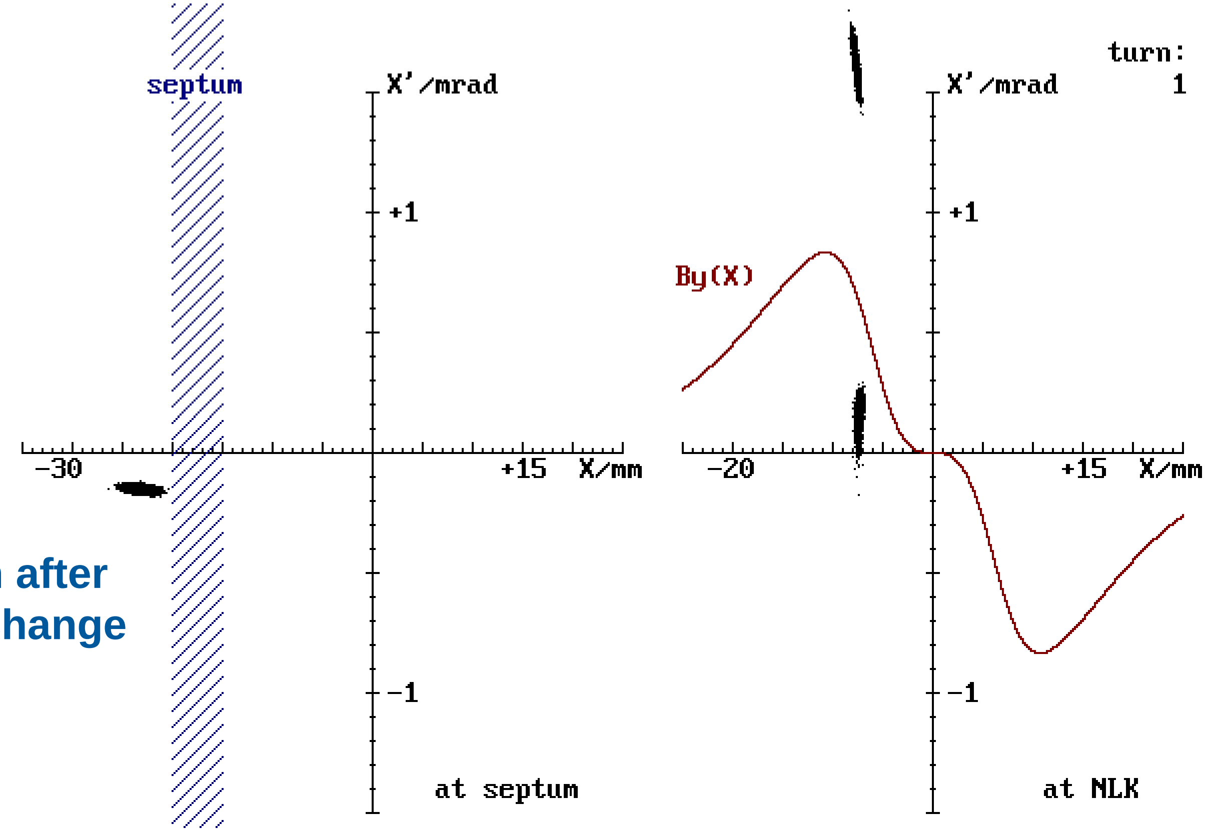
horizontal phase space



injected beam after emittance exchange

Appropriate phase advance between injection point and NLK or adjustment of injection angle

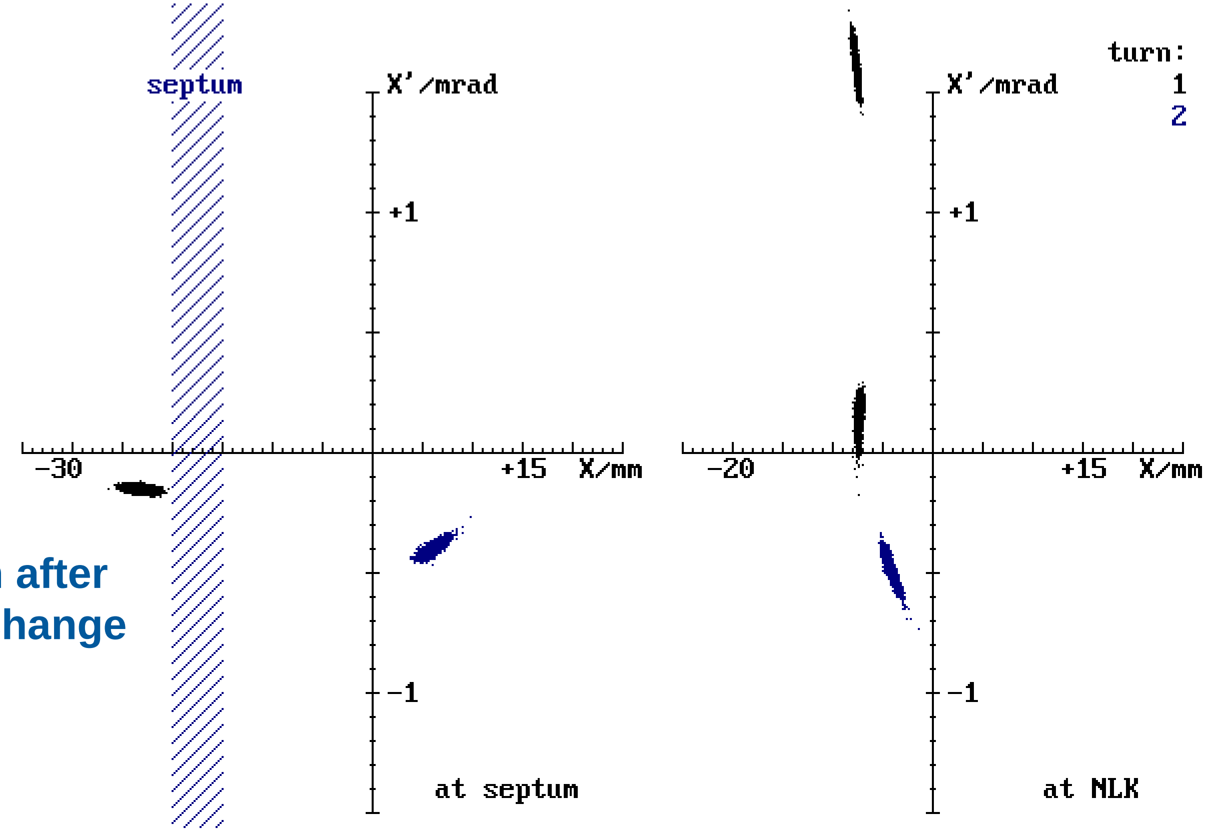
horizontal phase space



injected beam after emittance exchange

Kick strength of NLK takes out transverse momentum of injected beam

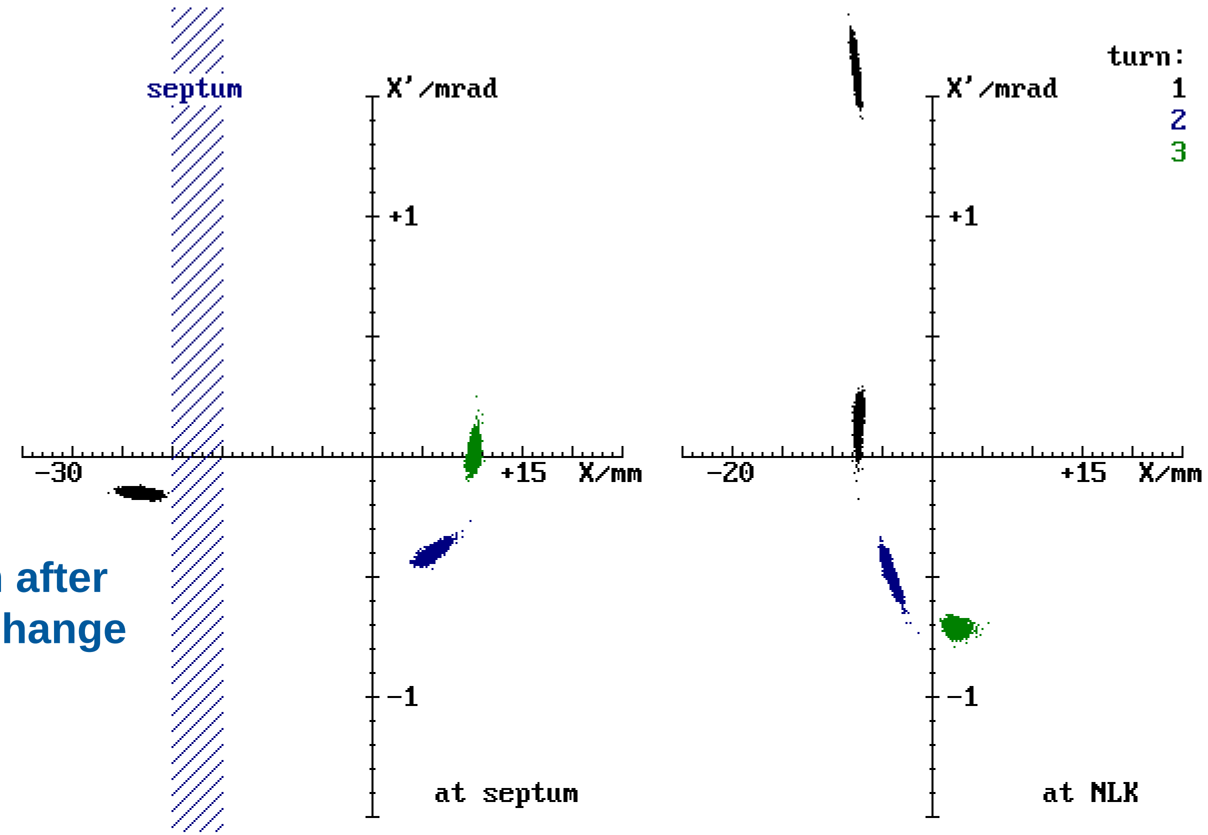
horizontal phase space



injected beam after emittance exchange

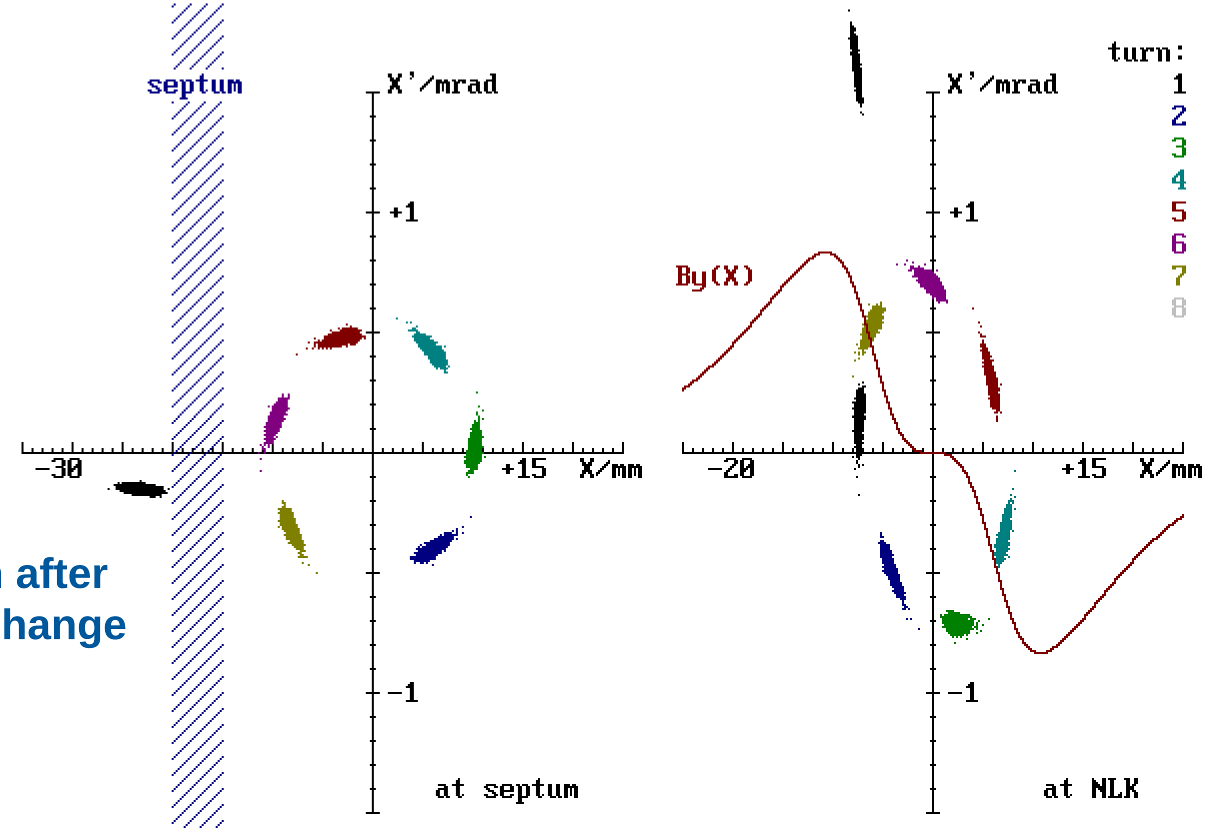
VI. Single Kicker Injection with Non-Linear Kicker

horizontal phase space



injected beam after emittance exchange

horizontal phase space



injected beam after emittance exchange

$ß_{NLK}$=$ß_{septum}$/2 – the current installation of the NLK in BESSY II

VI.1 Optimization

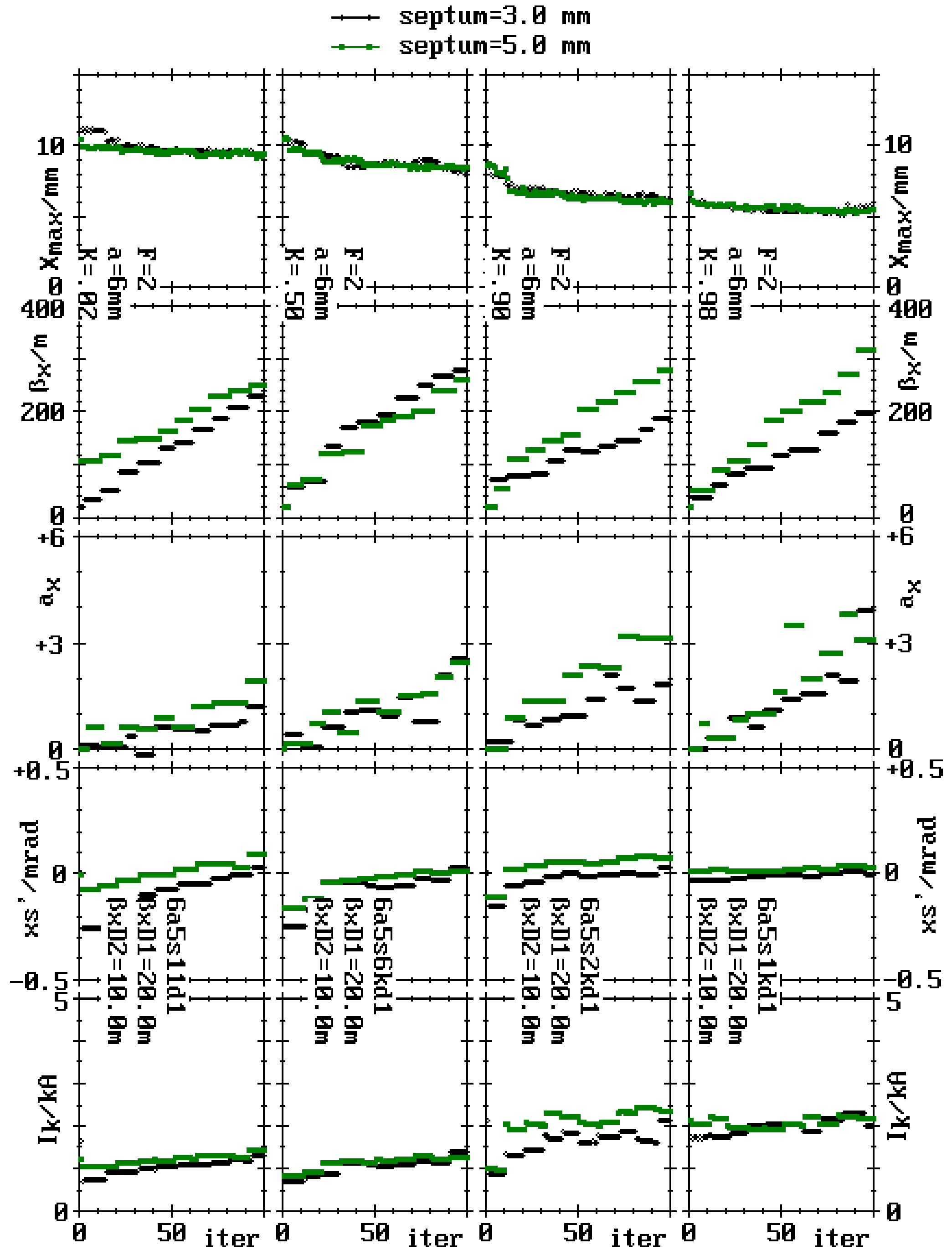
6 mm distance between wires

Non-linearity of the kicker requires numerical optimization

Results:

- **larger ß-values lead to smaller needed apertures**
- **non-zero α-values help**
- **with emittance exchange limit by vertical particle loss**
- **septum does not play a role**

Not really surprizing as the NLK itself is septum-like with no field on-axis.



VI.1 Optimization

7 mm distance between wires

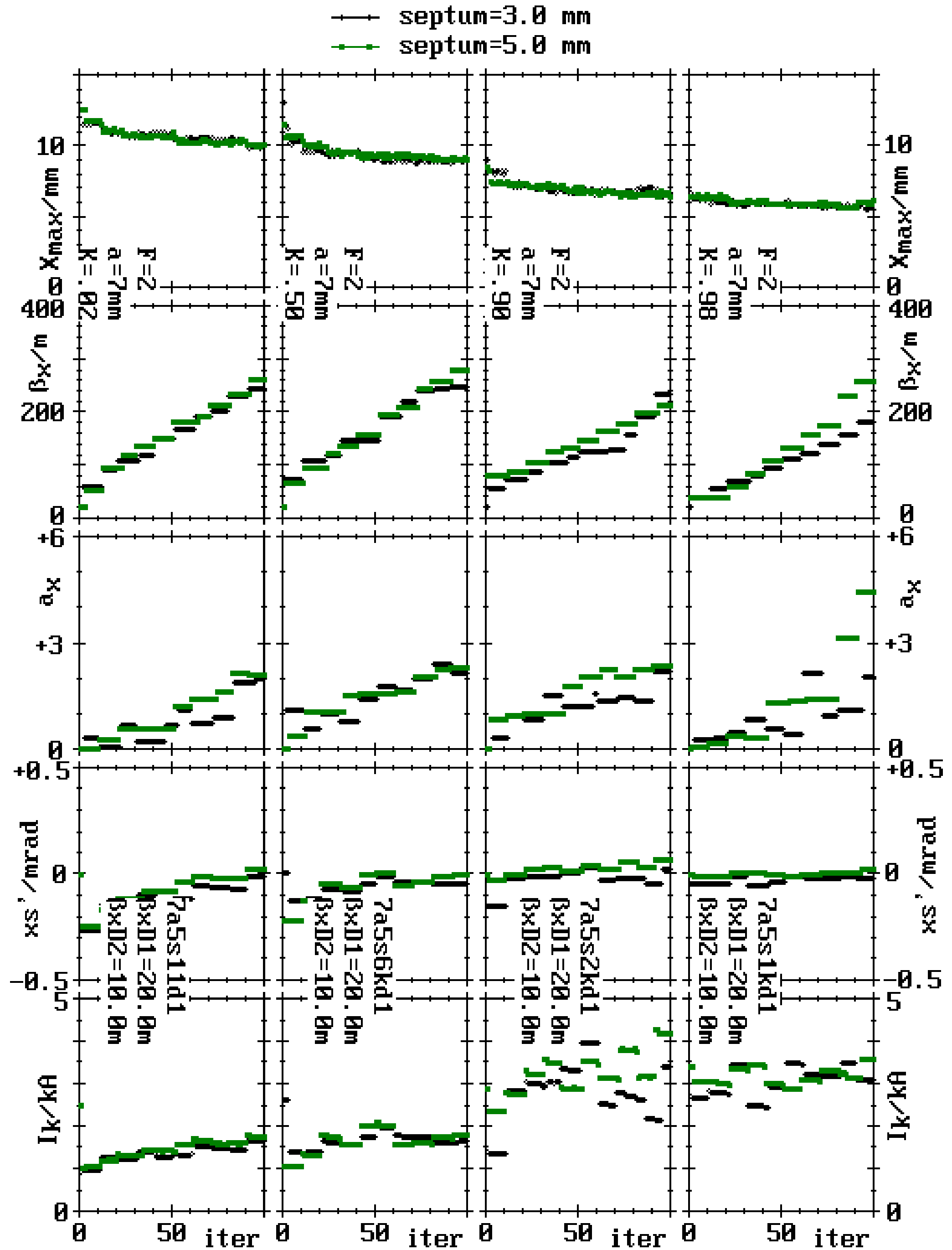
Non-linearity of the kicker requires numerical optimization

Results:

- **larger ß-values lead to smaller needed apertures**
- **non-zero α-values help**
- **with emittance exchange limit by vertical particle loss**
- **septum does not play a role**

Not really surprizing as the NLK itself is septum-like with no field on axis.

Larger distance between the wires = larger vertical gap leads to higher currents and slightly increased needed apertures



In the symmetric NLK there is always a location of the stored beam where the net kick for the bunch is zero. Perturbations in terms of still existing gradient, sextupole or octupole components will degrade the performance of the device. They scale with the value of ß$_0$ at the kicker.

These results are derived with the help of the Σ-matrix:

$$\Sigma_0 = \begin{pmatrix} \langle x_0 x_0 \rangle & \langle x_0 x_0' \rangle \\ \langle x_0 x_0' \rangle & \langle x_0' x_0' \rangle \end{pmatrix} = \begin{pmatrix} \beta_0 & -\alpha_0 \\ -\alpha_0 & \gamma_0 \end{pmatrix} \cdot \varepsilon_0$$

$$\Sigma_2 = R \cdot \Sigma_1 \cdot R^t$$

$$\varepsilon_0^2 = \langle x_0' x_0' \rangle \langle x_0 x_0 \rangle - \langle x_0 x_0' \rangle^2$$

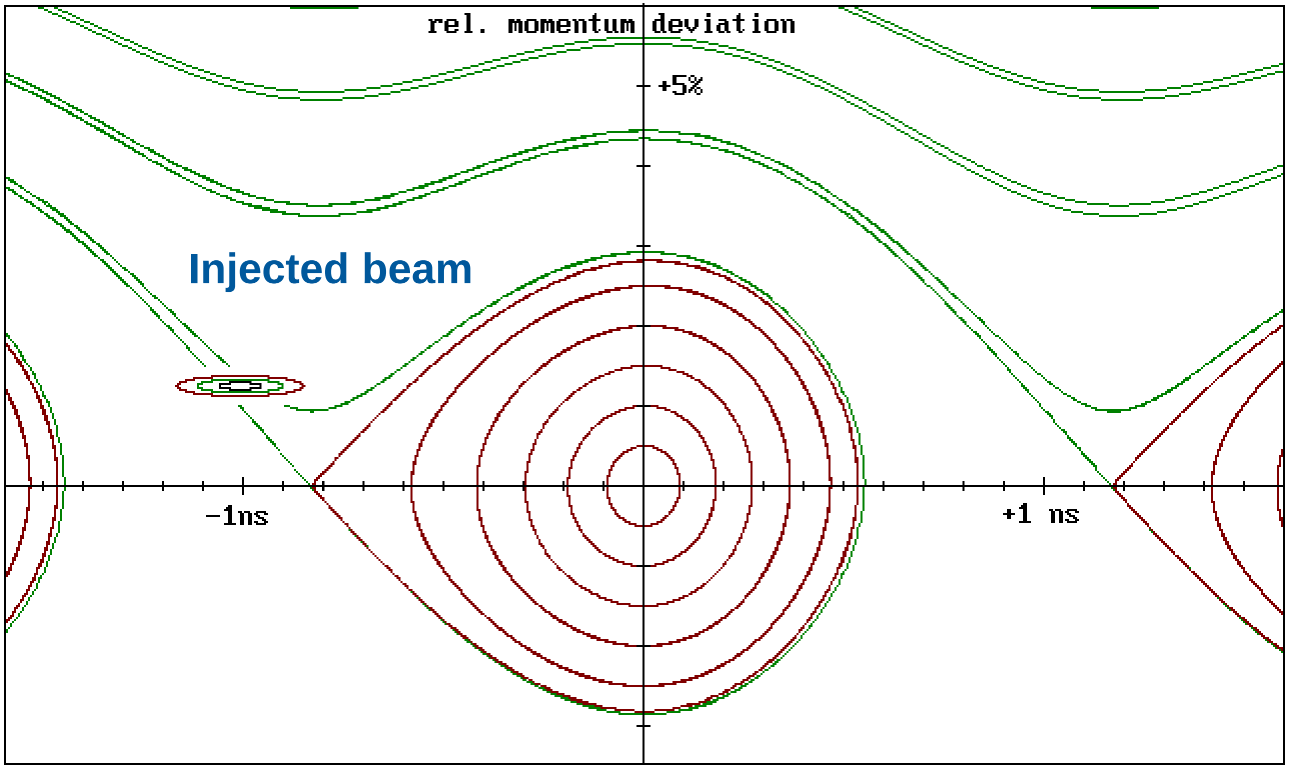
$$K = \frac{\frac{\partial B_y}{\partial x} L}{B\rho} \qquad x_1' = x_0' + K \cdot x_0 \qquad \frac{\sigma_x}{\sigma_{x_0}} \approx 1 \pm \frac{K \cdot \beta_0}{2}$$

$$S = \frac{\frac{\partial^2 B_y}{\partial x^2} L}{B\rho} \qquad x_1' = x_1' + \frac{S}{2} \cdot \qquad \frac{\varepsilon_1}{\varepsilon_0} \approx 1 + \frac{S^2}{4} \beta_0^3 \varepsilon_0$$

$$O = \frac{\frac{\partial^3 B_y}{\partial x^3} L}{B\rho} \qquad x_1' = x_1' + \frac{O}{6} \cdot x_0^3 \qquad \frac{\sigma_x}{\sigma_0} \approx 1 + \frac{O}{4} \beta_0 \sigma_0^2 = 1 + \frac{O}{4} \beta_0^2 \varepsilon_0$$

$$\frac{\varepsilon_1}{\varepsilon_0} \approx 1 + \frac{O^2}{12} \beta_0^4 \varepsilon_0^2$$

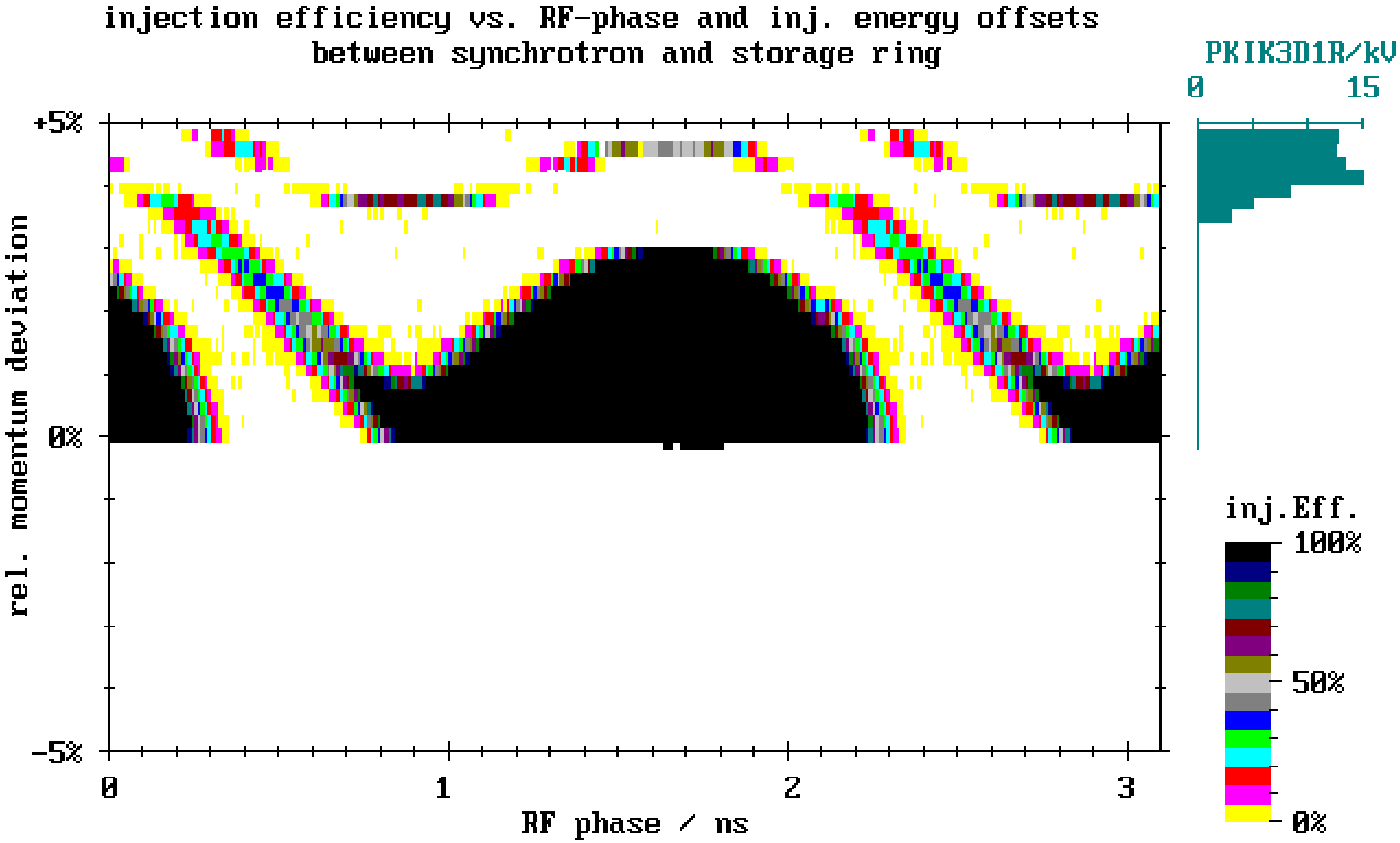
standard RF-settings + injected beam parameters as delivered by the BESSY II synchrotron



Contributions to the Topical Workshop on Injection and Injection Systems, 28-30 August 2017, Berlin, *https://indico.cern.ch/event/635514:*

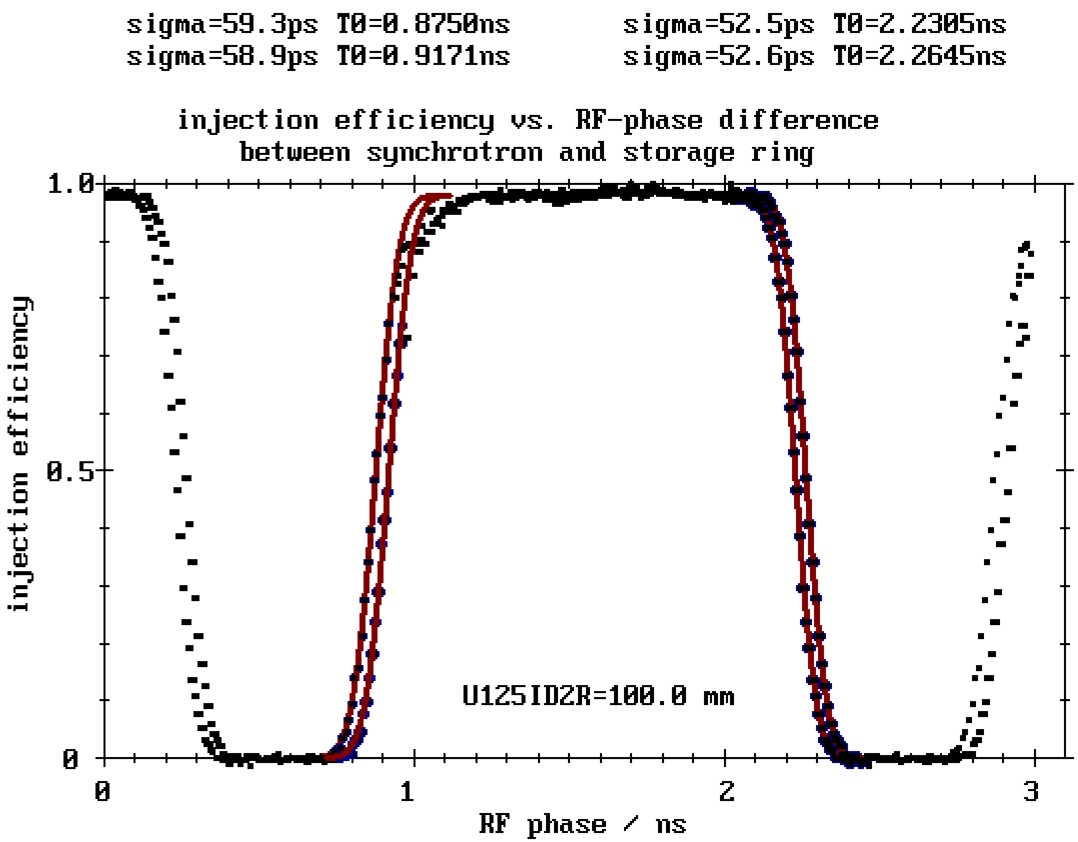
- M. Aiba, et al., Longitudinal Top-Up Injection for Small Aperture Storage Rings
- Zhe Duan, Injection Schemes For HEPS
- Gang Xu, Longitudinal accumulation in triple RF systems
- M.-A Tordeux, Longitudinal injection into low-emittance ring: A novel scheme for SOLEIL upgrade

BESSY II – nominal settings – on-axis injection with diagnostics kicker – injection energy varied by extracting earlier or later (synchrotron works with White-circuits) – phase variation with trombone – swap-out injection



VII. Longitudinal Parameters of the Injected Beam

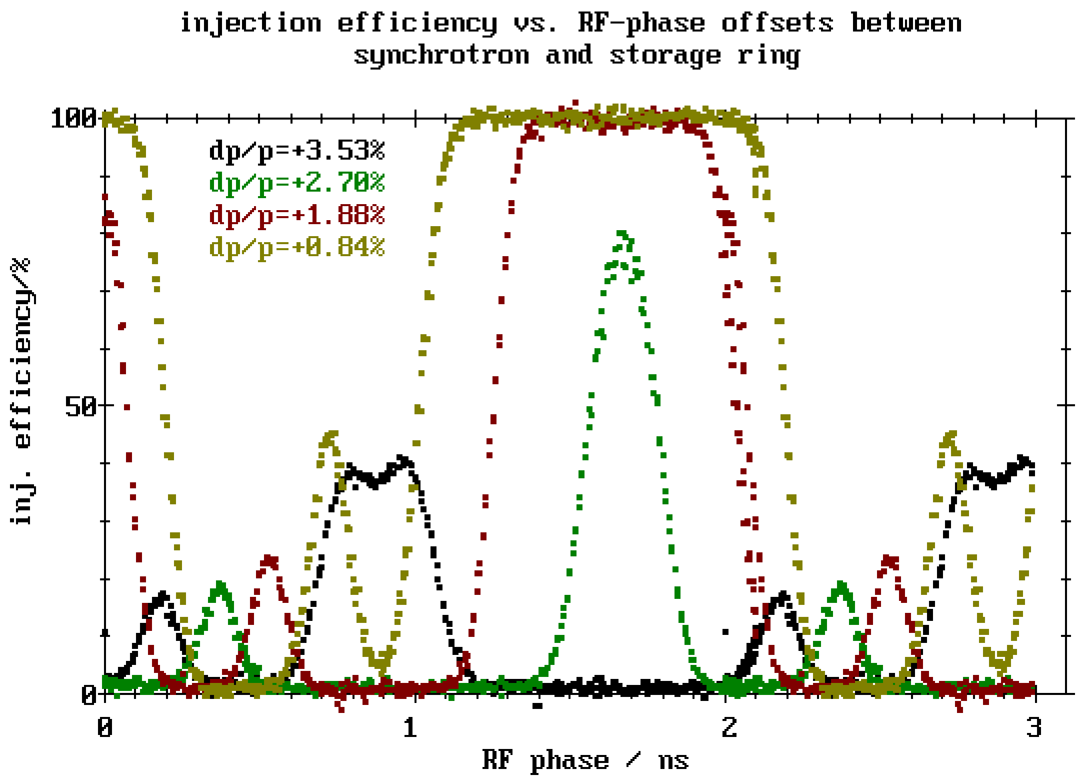
Theory: $\sigma \sim 60$ ps, $\sigma_\varepsilon \sim 5.7 \cdot 10^{-4}$ - measurement: 55±4ps from phase scans, $\sigma_\varepsilon \sim 6 \cdot 10^{-4}$ from quadrupole scans in the transferline



Phase acceptance scan with on-momentum injection

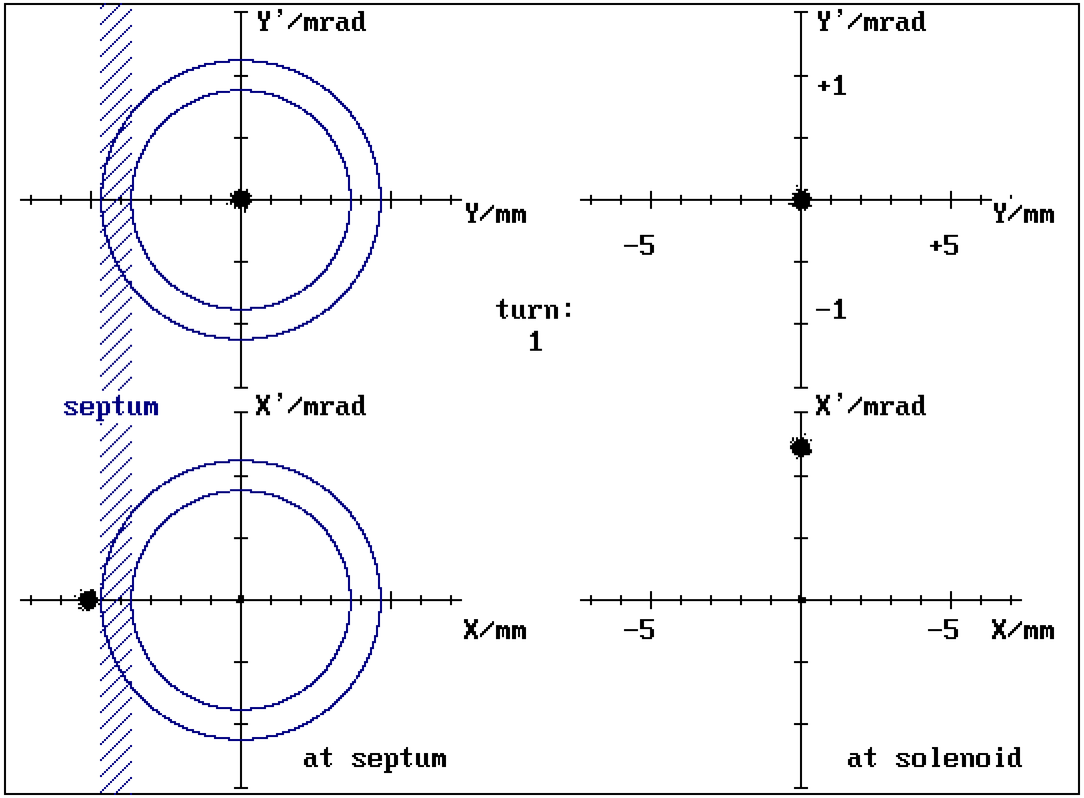
VII. Phase Acceptance Scans Off-Momentum

Width of „acceptance lines“ and edges of acceptance are dominated by the large bunchlength

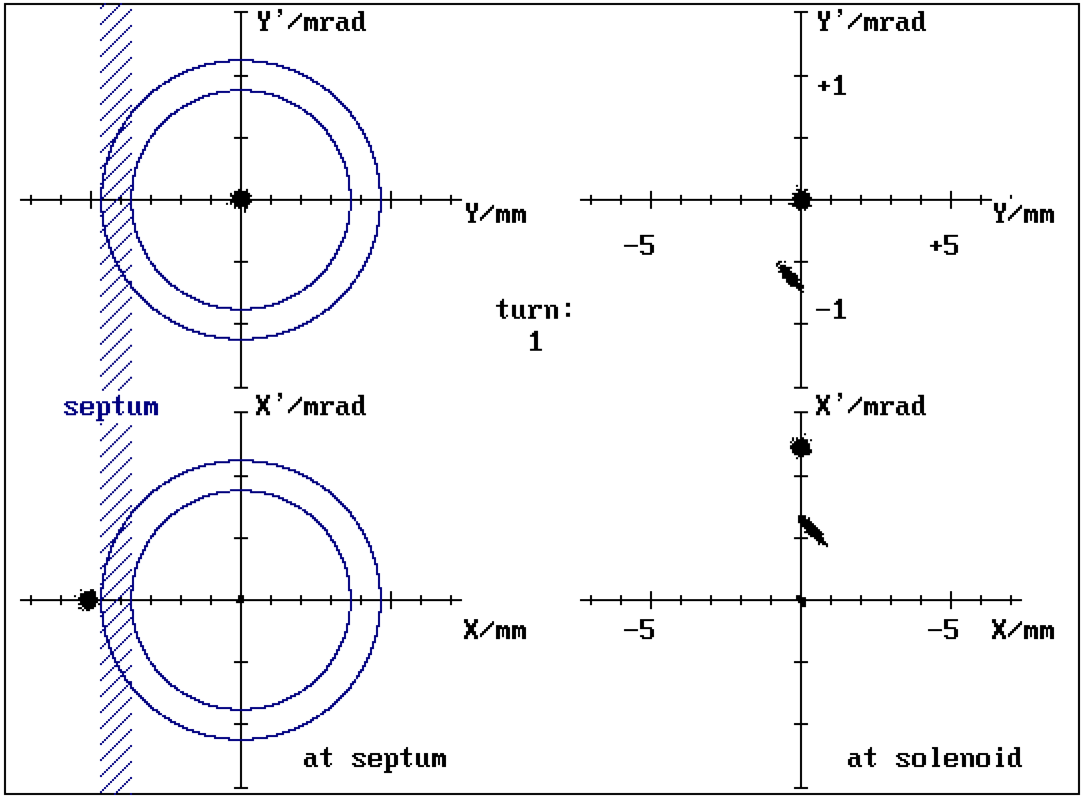


Longitudinal injection schemes require an adequate longitudinal emittance of the injected beam.

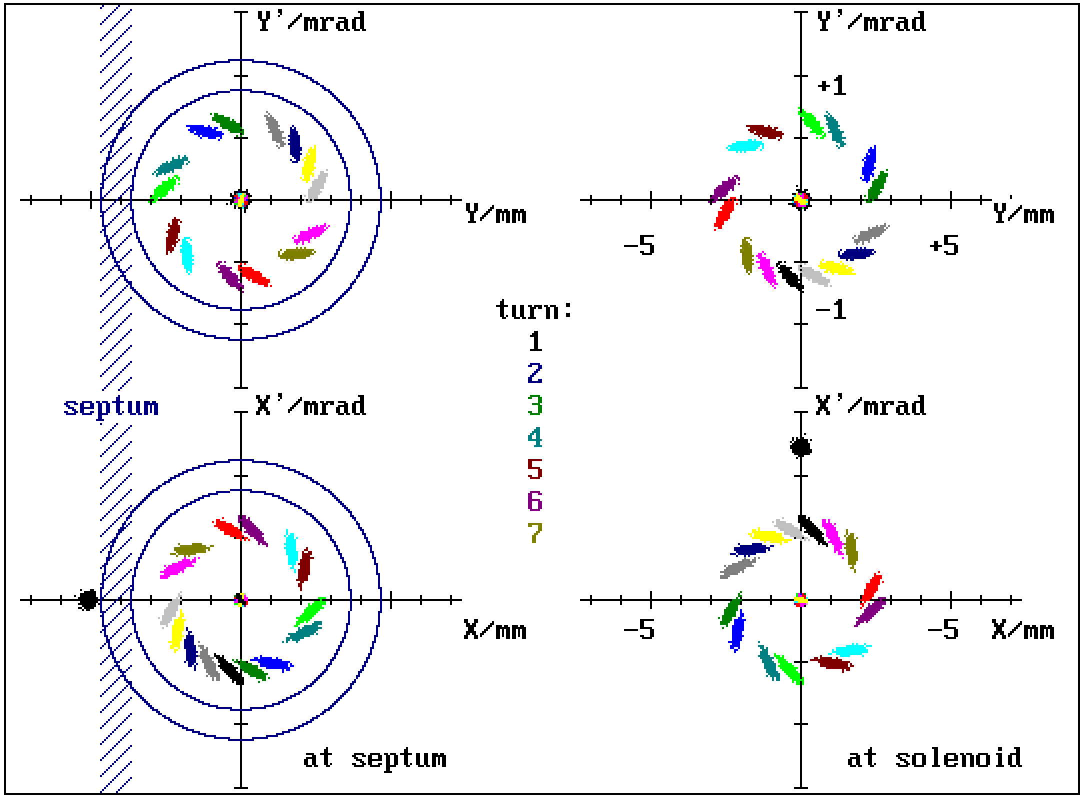
Using a pulsed solenoid to transfer horizontal momentum to the vertical plane.



Using a pulsed solenoid to transfer horizontal momentum to the vertical plane.



Using a pulsed solenoid to transfer horizontal momentum to the vertical plane.



injection scheme	septum	kicker	on-axis	stored beam excitation	transparent	example
transverse:						
position	yes	1-4 or NLK	no	not with NLK	with NLK	II, III, IV,VI
angle	yes	1-4 or NLK	no	not with NLK	with NLK	III,VI
both	yes	NLK	no	no	yes	VI
longitudinal:						
phase	yes	stripline	yes	no	yes	VII
momentum	yes	stripline or NLK	yes	no	yes	VII
both	yes	stripline or NLK	yes	no	yes	VII
Swap-out	yes	stripline	yes	yes/pre-kick	yes	V

All schemes require at least 1 septum magnet – the thinner the septum blade the better. All schemes profit from small or at least adequate 6d-emittance of injected beam – injection efficiency and ease of realization.

injection scheme	septum	kicker	on-axis	stored beam excitation	transparent	example
transverse:						
position	yes	1-4 or NLK	no	not with NLK	with NLK	II, III, IV,VI
angle	yes	1-4 or NLK	no	not with NLK	with NLK	III,VI
both	yes	NLK	no	no	yes	VI
longitudinal:						
phase	yes	stripline	yes	no	yes	VII
momentum	yes	stripline or NLK	yes	no	yes	VII
both	yes	stripline or NLK	yes	no	yes	VII
Swap-out	yes	stripline	yes	yes/pre-kick	yes	V

All schemes require at least 1 septum magnet – the thinner the septum blade the better. All schemes profit from small or at least adequate 6D-emittance of injected beam – injection efficiency and ease of realization.

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with reduced RF cavity voltage and smaller momentum acceptance